

# 3D Design for 3D Printing

Mike Horwath

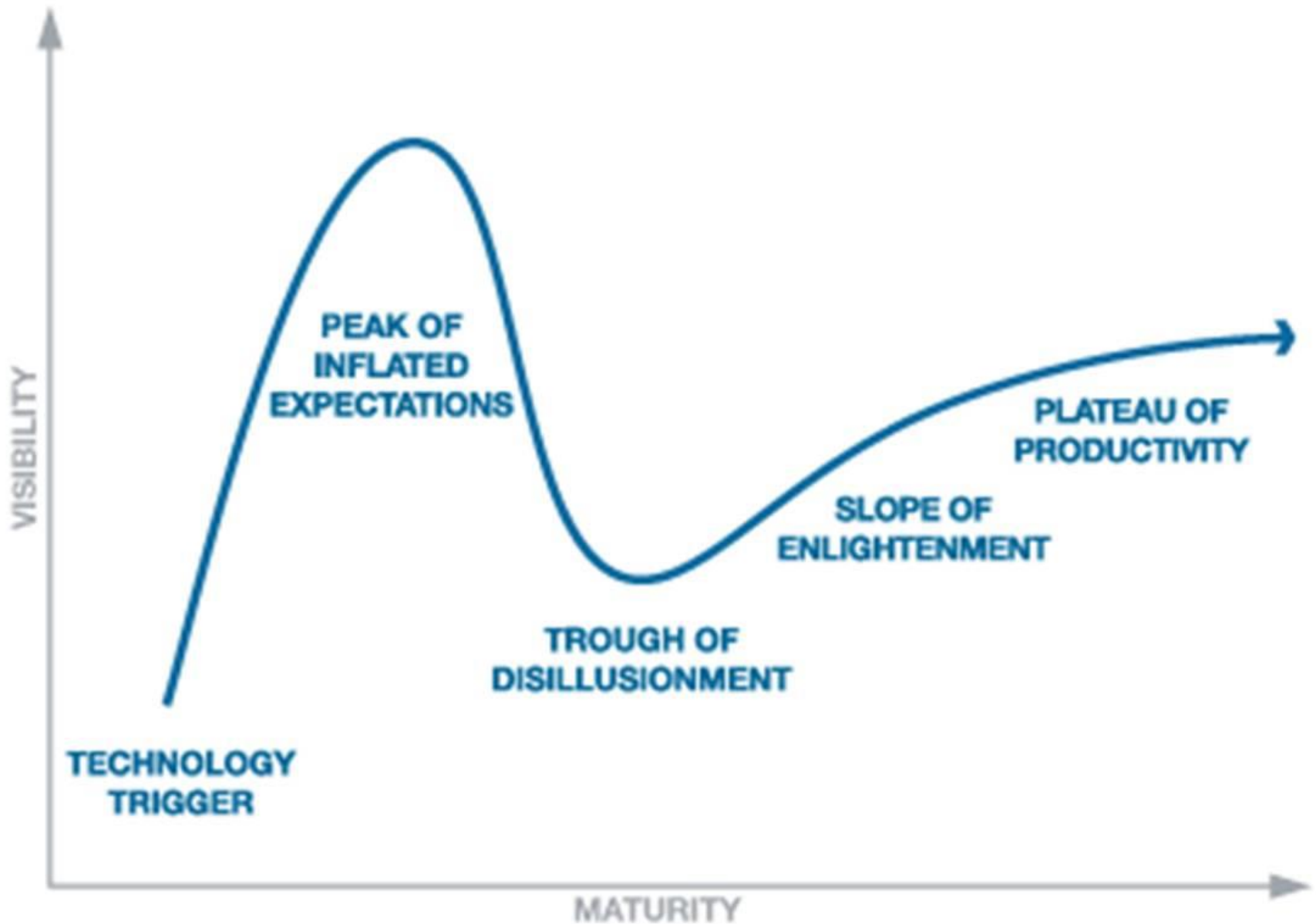
Sept 2016

# Outline

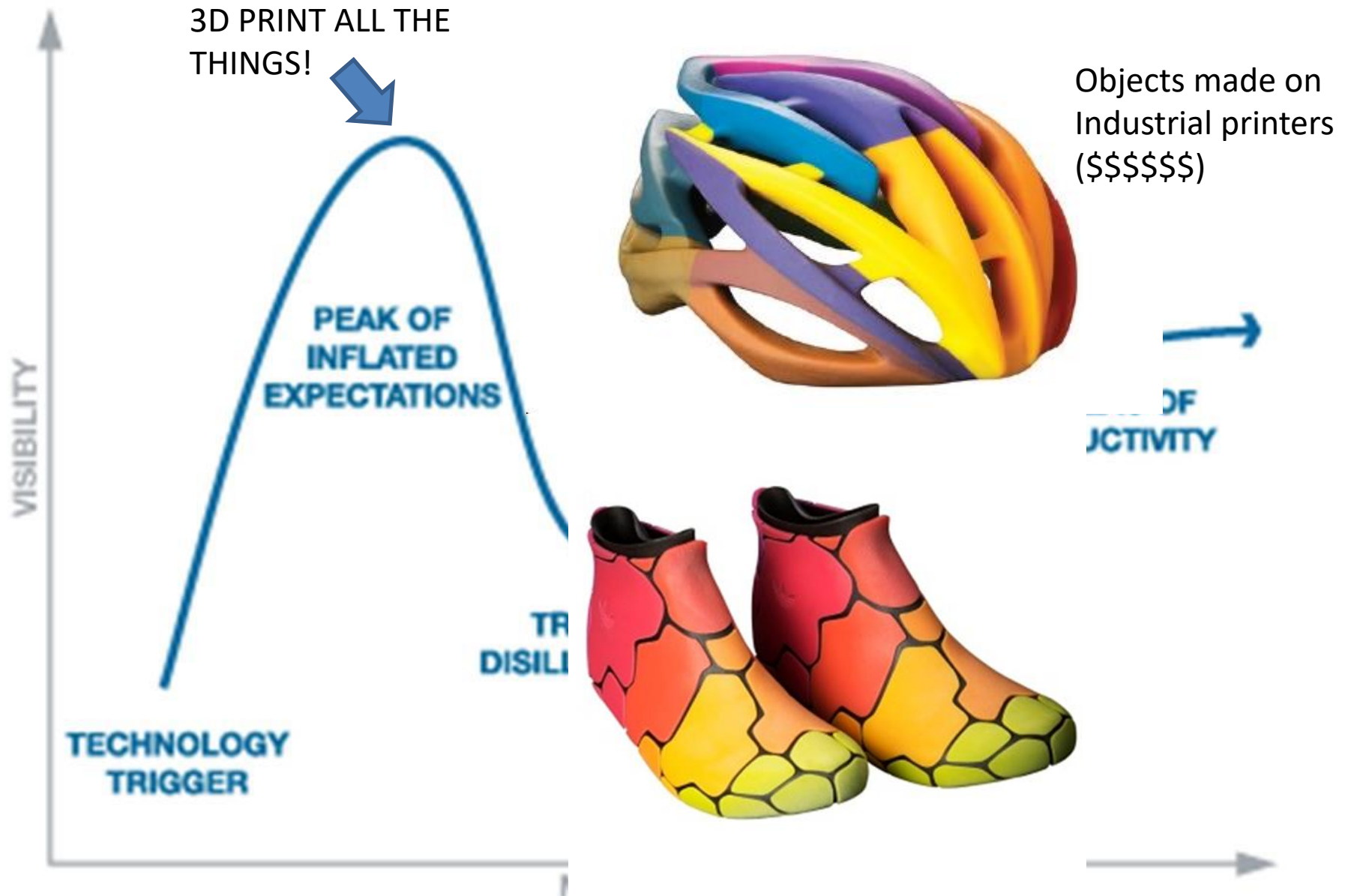
1. Design?
2. Tools for CAD (more engineering-ish)
3. Tools for 3D modelling (more artsy)
4. General tips for designing for 3D printing

# Why Learn Design?

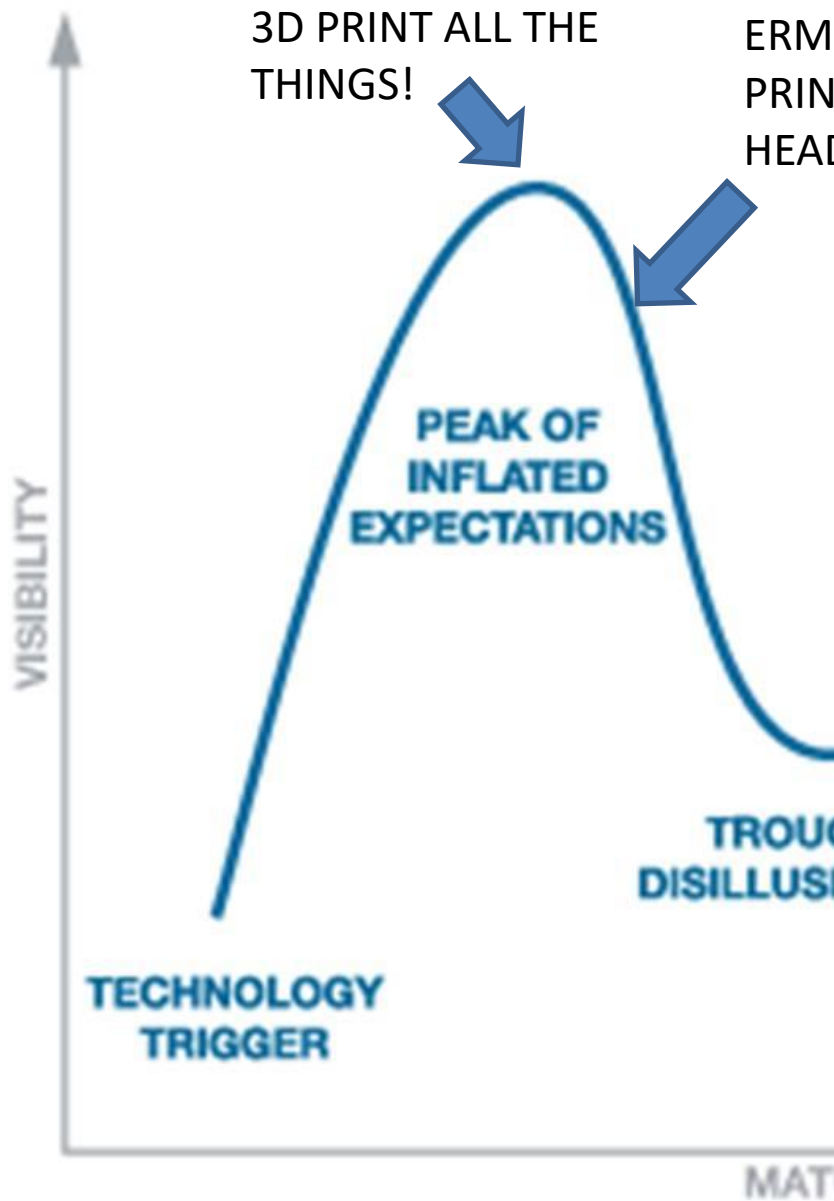
# Technology Hype Cycle



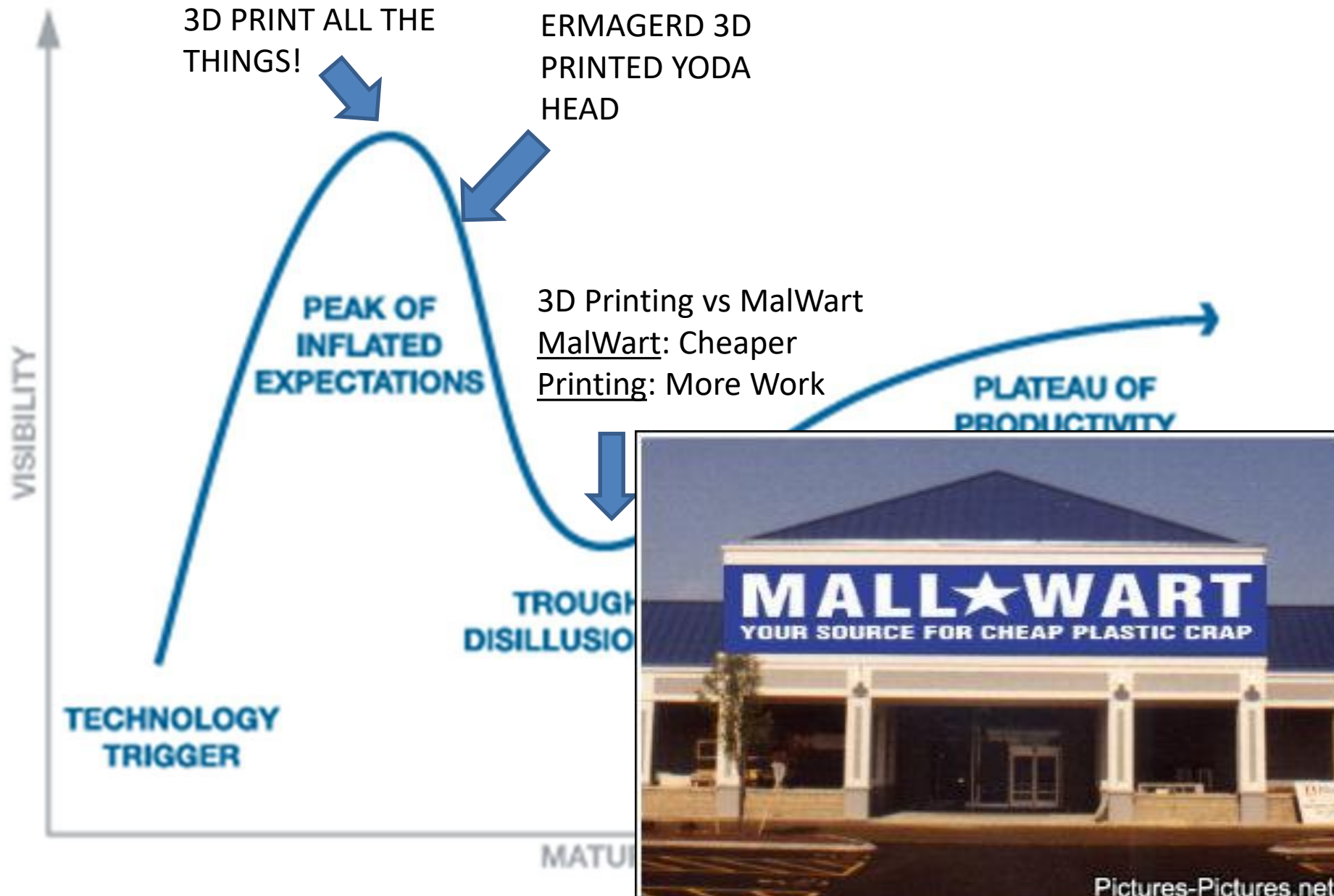
# “Desktop” 3D Printing Hype Cycle



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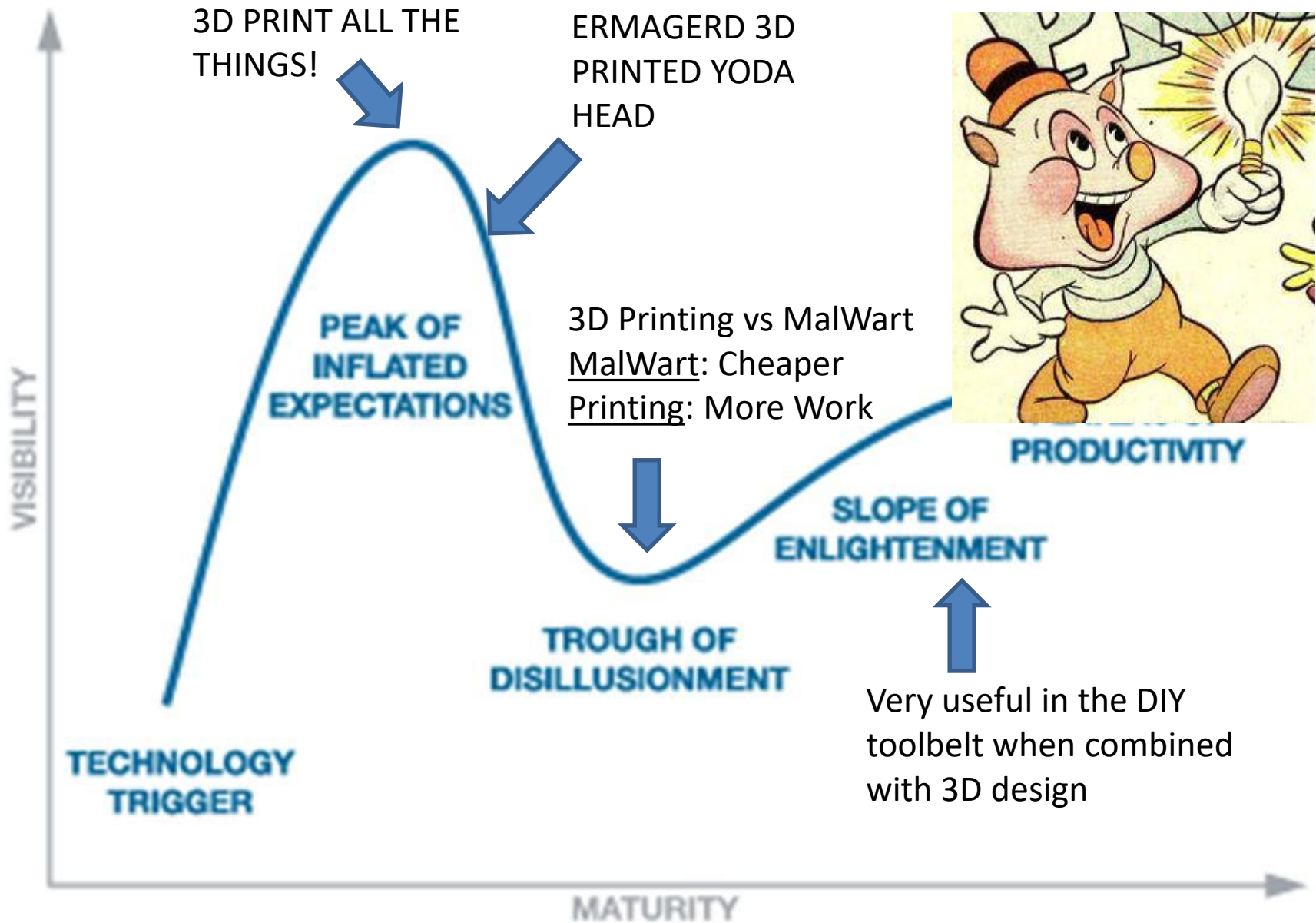


# “Desktop” 3D Printing Hype Cycle



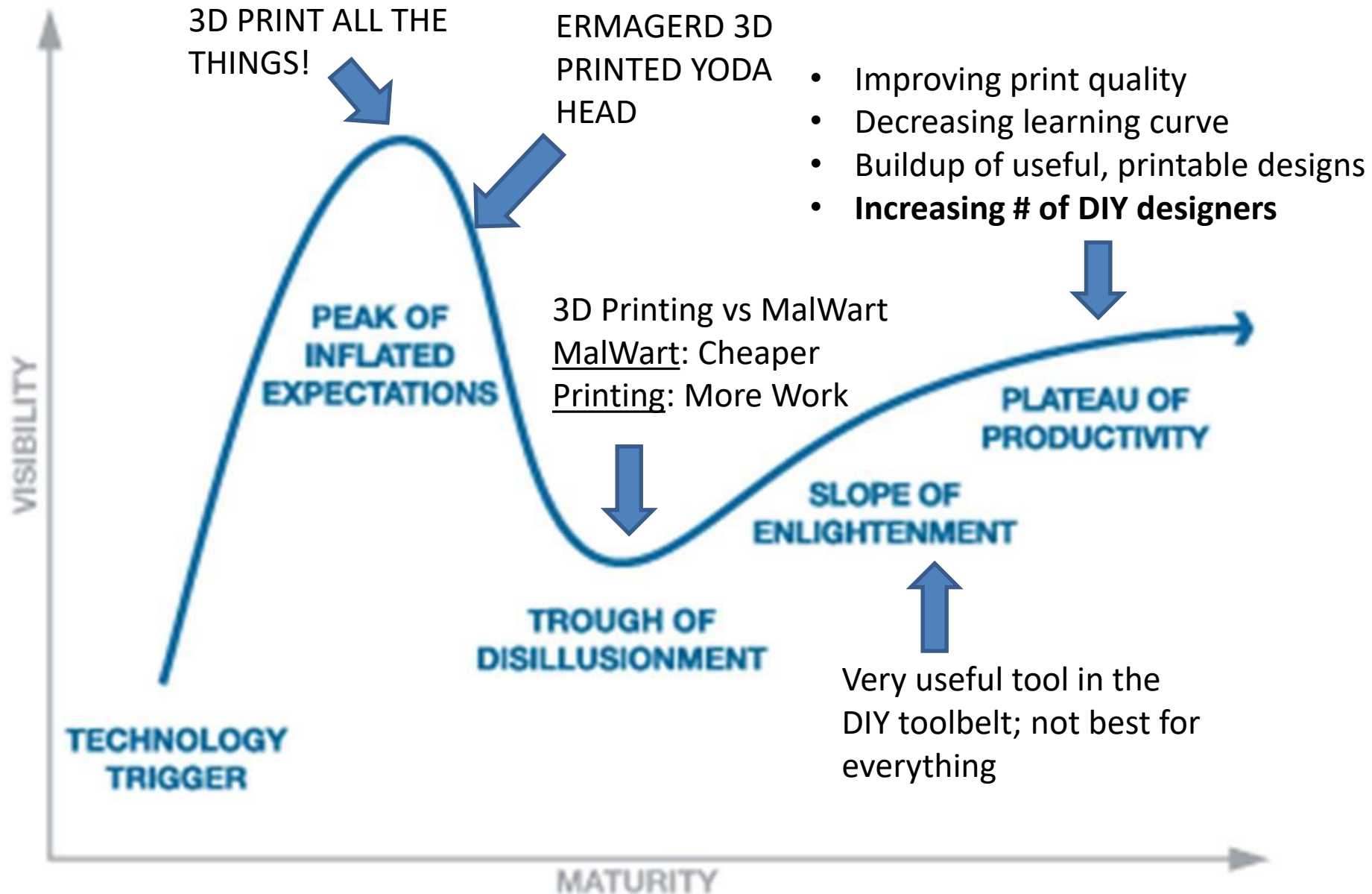


# “Desktop” 3D Printing Hype Cycle





# “Desktop” 3D Printing Hype Cycle

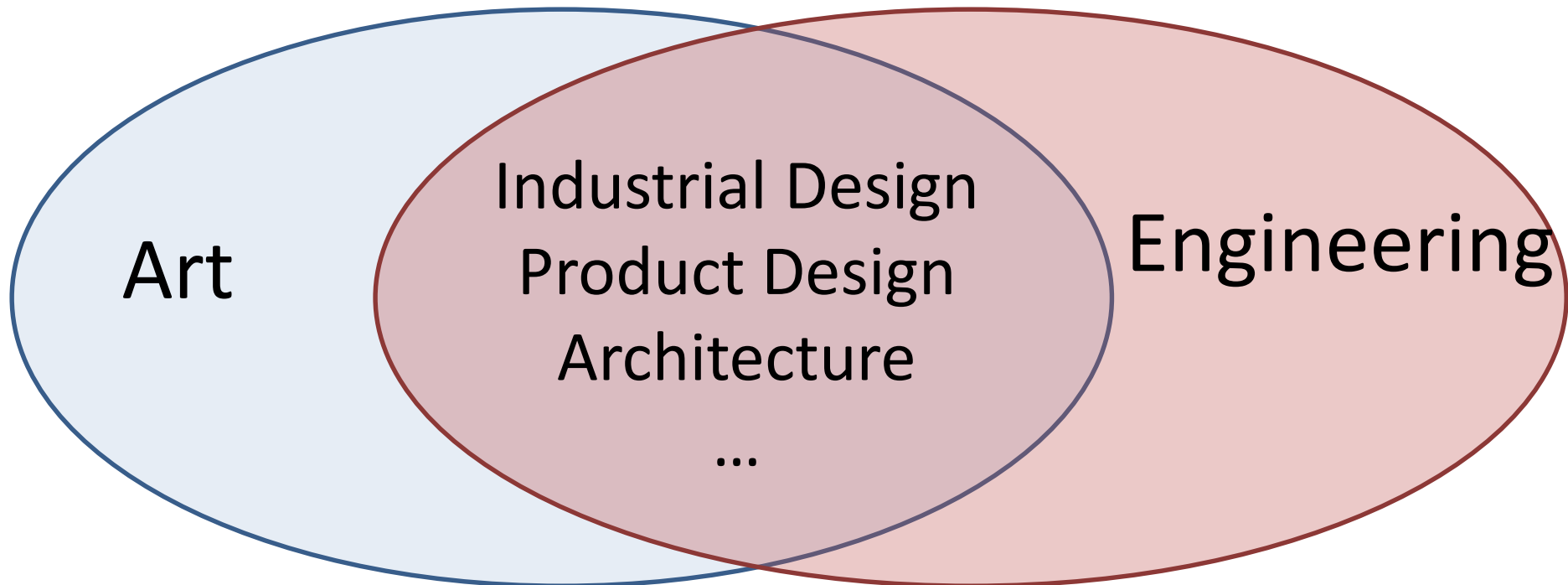


# What is Design?

Design = Development of an Idea into a Thing

Design of physical things takes into account:

- Function or purpose
- User interaction/experience
- Material
- Manufacturing Process

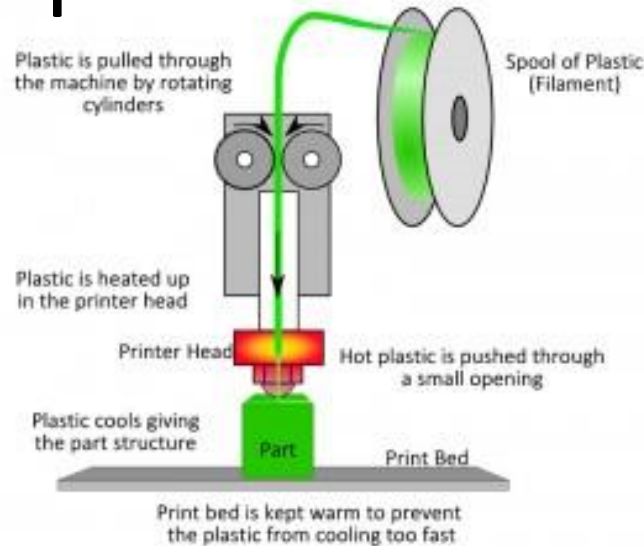


# Speaking of Manufacturing Process:

## Fused Filament Fabrication (FFF)

*aka*

## Thermoplastic Extrusion



This is the most common type of Fused Deposition Modeling (FDM), which also includes things like paste extrusion and polyjet

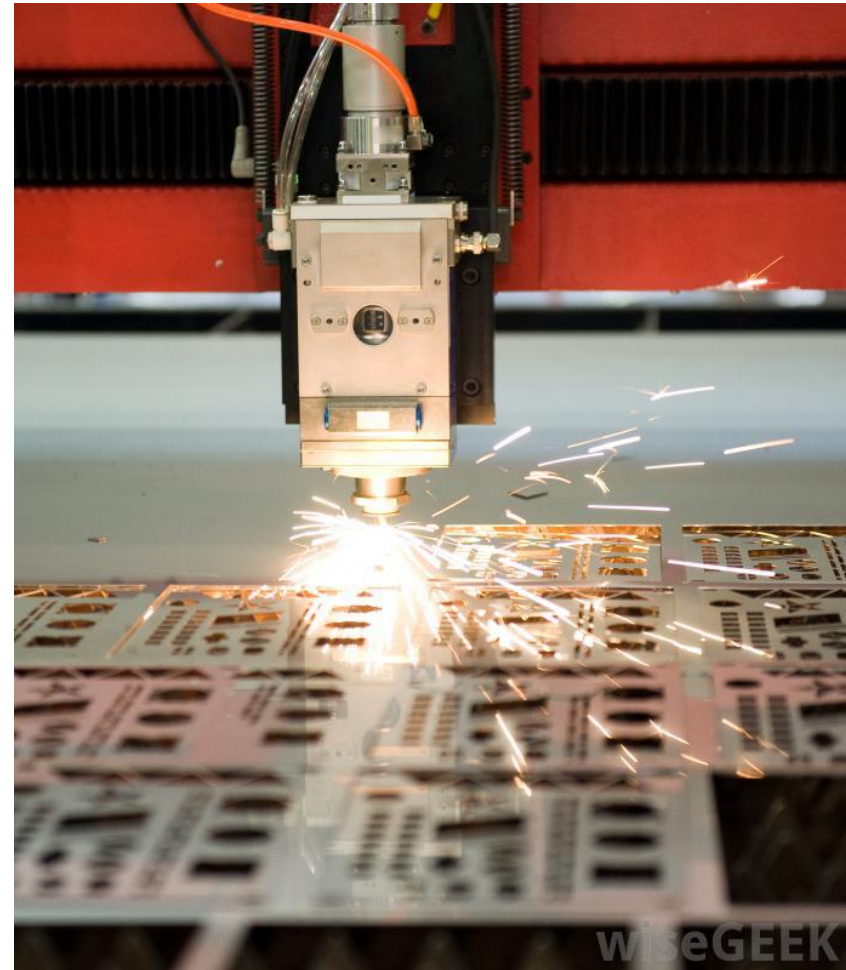
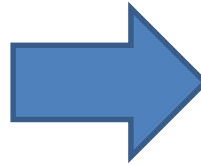
# Different Tools for Different Needs

- Computer-Assisted Design (CAD)
  - Digital representation that accurately defines a physical object
  - Focus on ability to guide manufacturing
- 3D Modelling
  - Digital objects created for images and animations that are not intended to become physical objects
  - Focus on ability to render and animate realistically
- Significant gray area between the two... sometimes used interchangeably

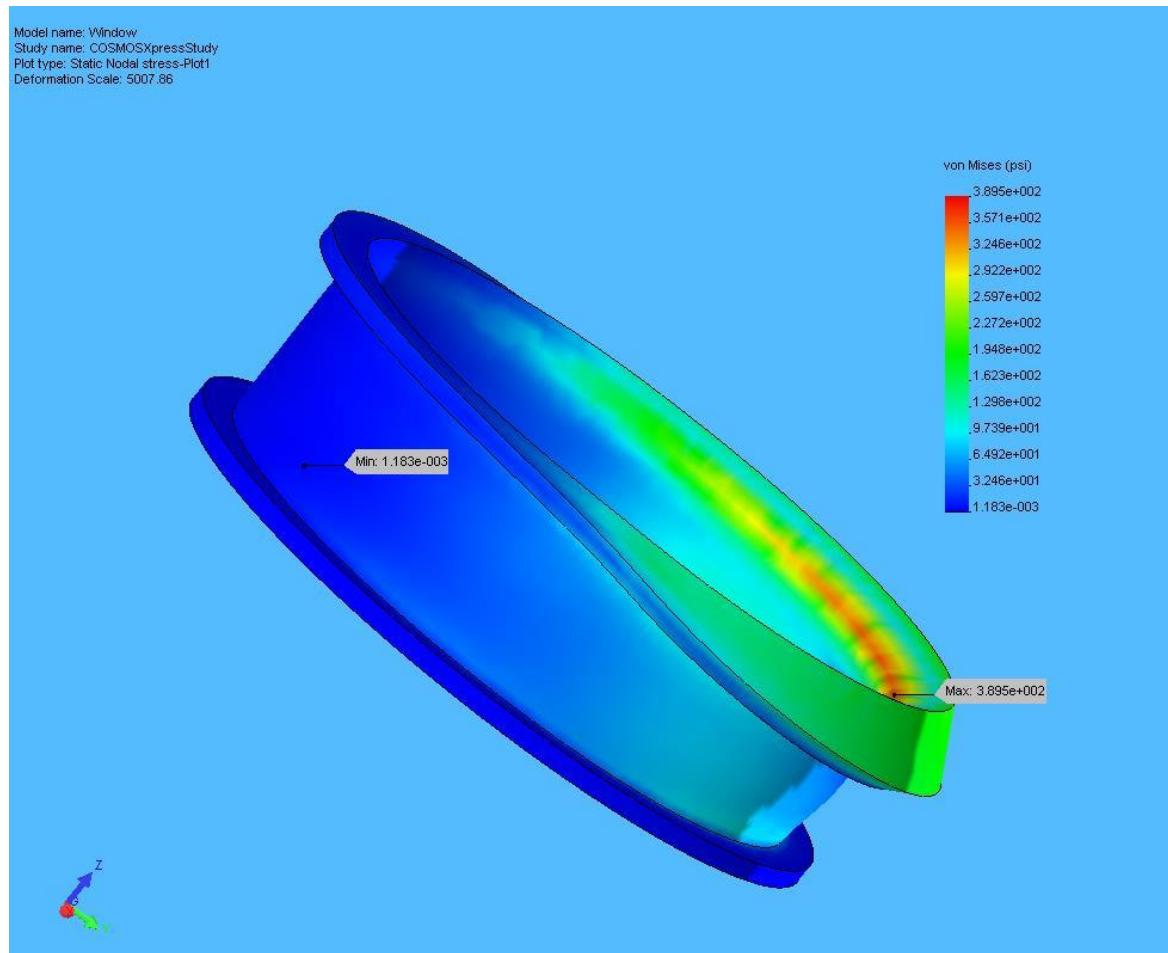
# CAM = Computer-Assisted Manufacturing

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M03 F200
G1 X-37.939 Y8.793 Z16.000
G1 X-37.939 Y8.793 Z6.000
G1 X-35.617 Y8.793 Z6.000
G1 X-34.780 Y8.748 Z6.000
G1 X-34.060 Y8.622 Z6.000
G1 X-33.448 Y8.379 Z6.000
G1 X-32.890 Y7.992 Z6.000
G1 X-31.855 Y6.516 Z6.000
G1 X-31.513 Y4.419 Z6.000
G1 X-31.549 Y3.663 Z6.000
G1 X-31.648 Y2.970 Z6.000
G1 X-31.828 Y2.349 Z6.000
G1 X-32.080 Y1.791 Z6.000
G1 X-32.404 Y1.296 Z6.000
G1 X-32.818 Y0.855 Z6.000
G1 X-33.187 Y0.567 Z6.000
G1 X-33.592 Y0.351 Z6.000
G1 X-34.024 Y0.180 Z6.000
G1 X-34.492 Y0.081 Z6.000
G1 X-35.005 Y0.018 Z6.000
G1 X-35.581 Y0.000 Z6.000
G1 X-37.903 Y0.000 Z6.000
G1 X-38.326 Y0.036 Z6.000
G1 X-38.632 Y0.144 Z6.000
G1 X-38.839 Y0.324 Z6.000
G1 X-38.956 Y0.558 Z6.000
G1 X-39.010 Y0.864 Z6.000
G1 X-39.028 Y1.251 Z6.000

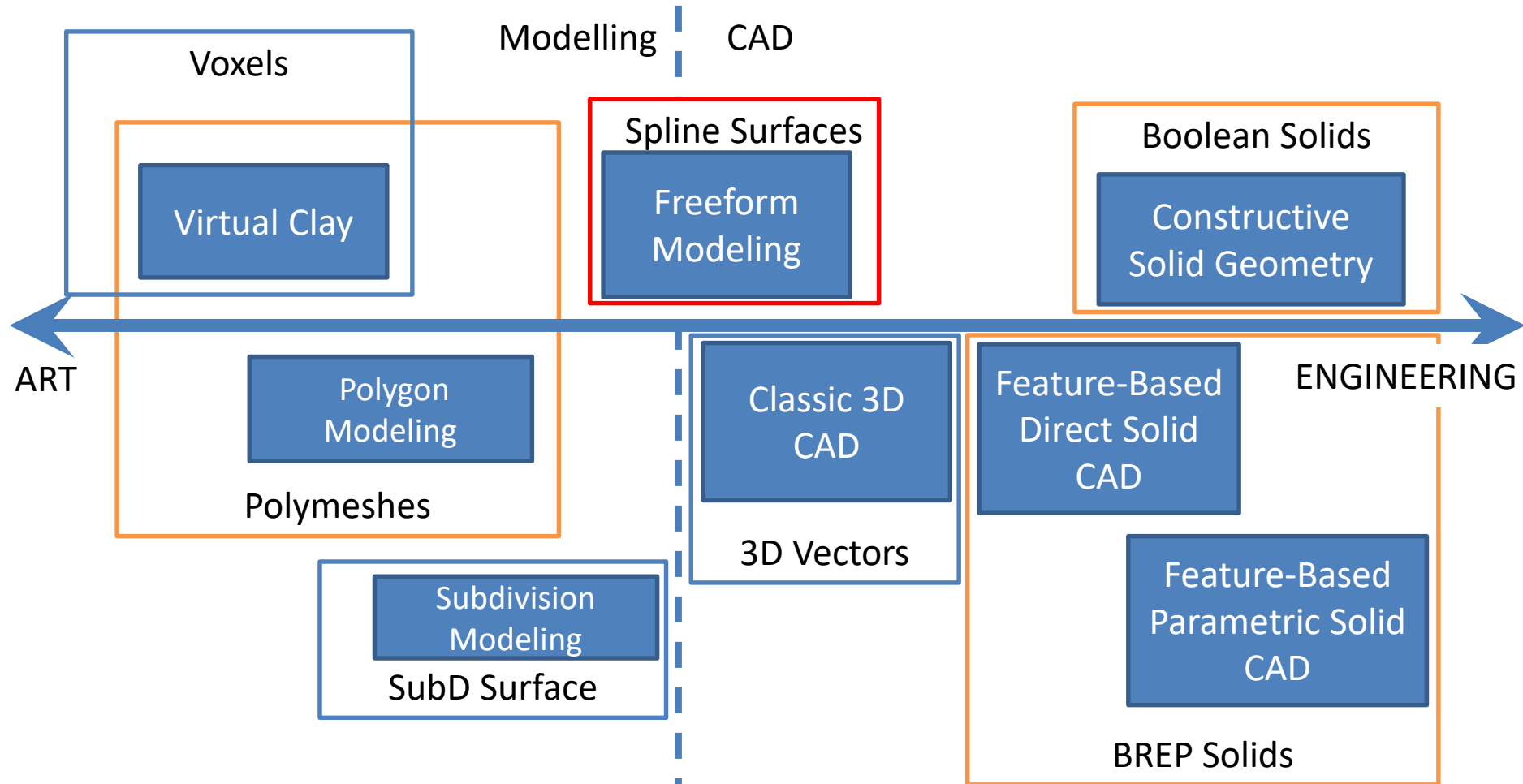
549 -STRAIGHT_FEED(41.9600, 7.8750,
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551 -STOP_SPINDLE_TURNING()@94580.1
```



# CAE = Computer-Assisted Engineering

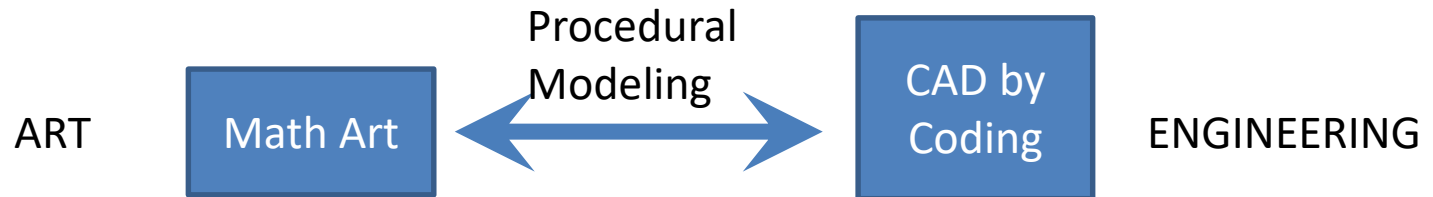


# Different Tools for Different Needs



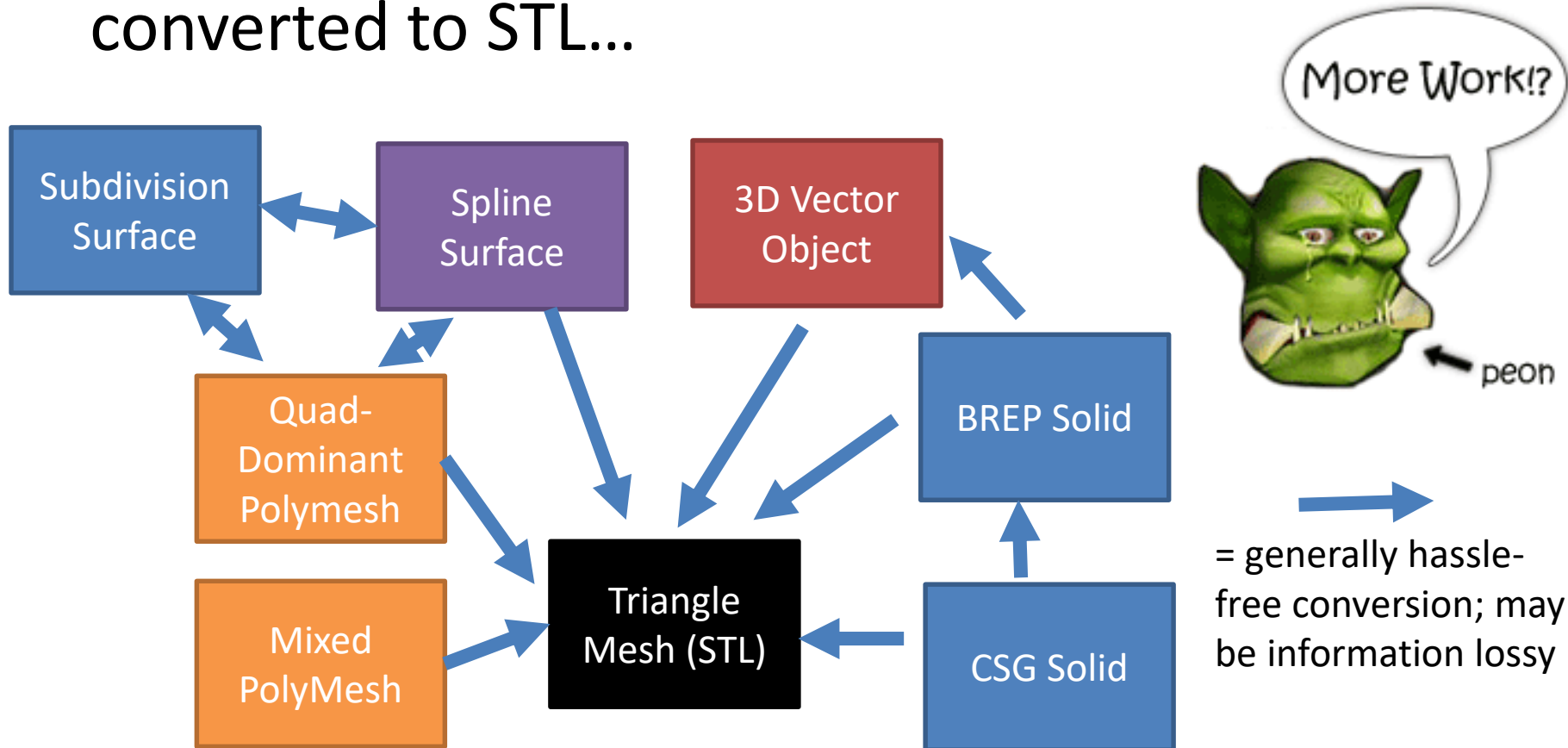


# Procedural modeling: Marsupial Evolution



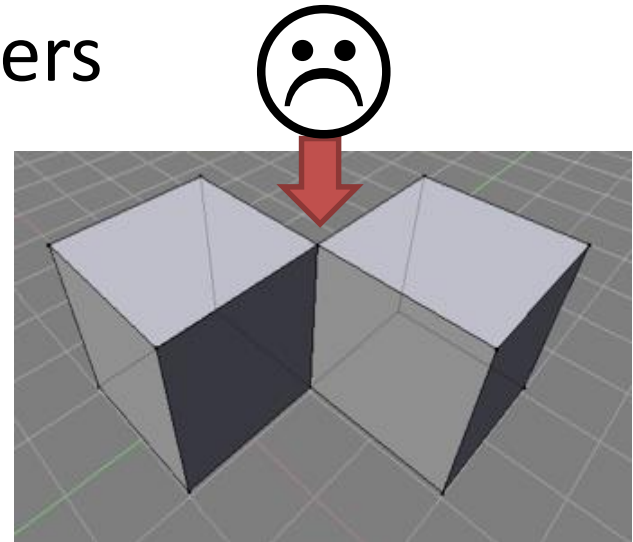
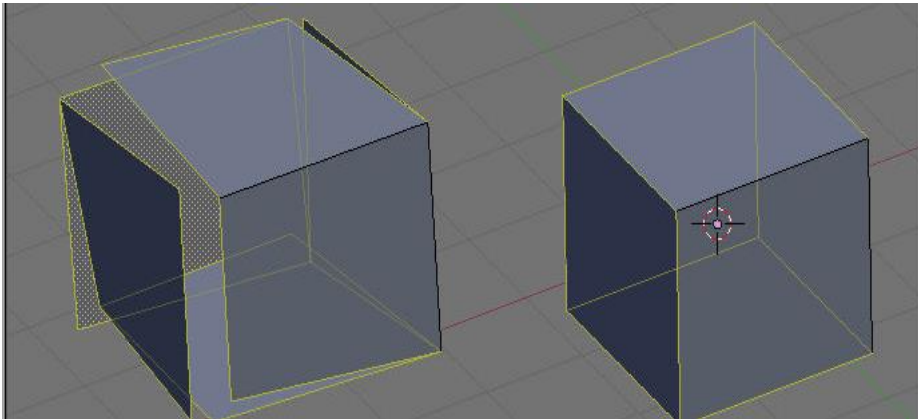
# STL: The Peon of 3D Printing

- Most 3D printing software accepts .STL (stupid-simple triangle mesh) as the input.
- However, pretty much everything else can be converted to STL...



# Make it Manifold!

- 1—Watertight (3D space fully enclosed)
- 2—No shared edges or corners



- Also avoid: self-intersection
- Most slicing software can work through minor issues

Usually OK



Problematic



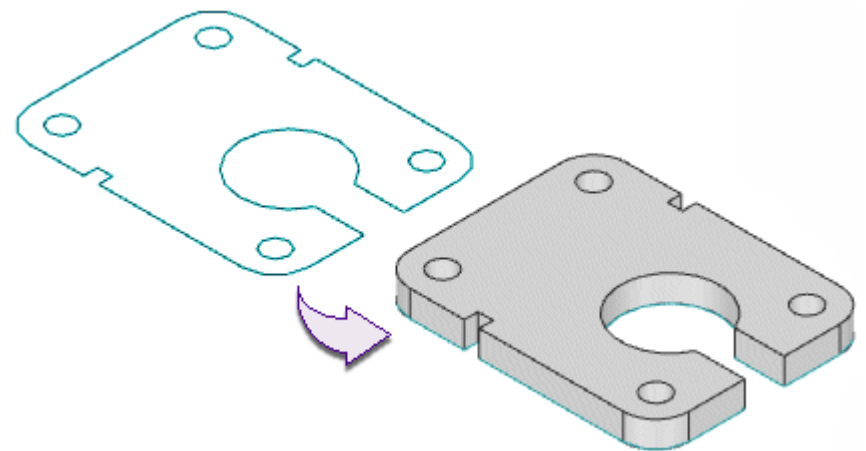
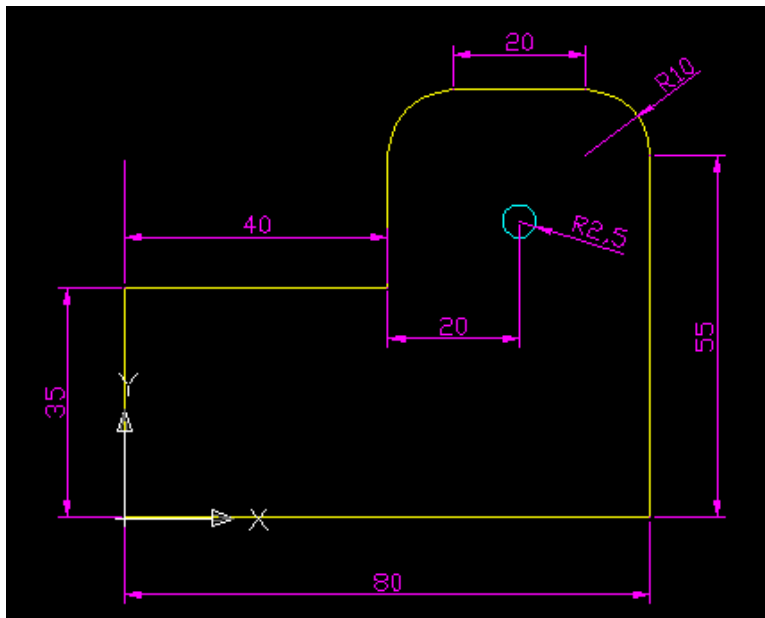
# Rapid Tour of Design Methods



- I'm not a pro, feel free to speak up if I'm screwing something up 😊
- Example programs are (1) free (2) I've personally found useful. Other good options are out there!

# Classic 3D CAD\*

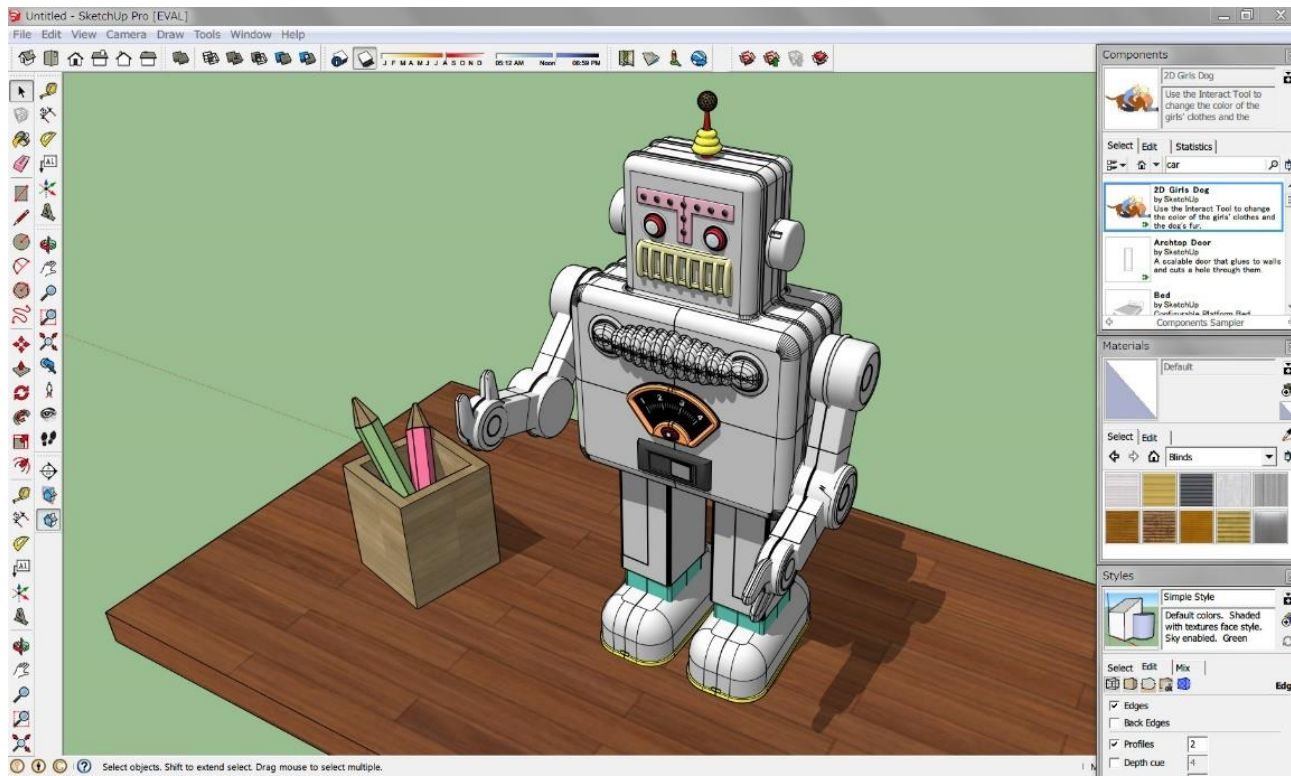
- Alternative definition of CAD: Computer Aided Drafting
- Evolution: pencil and paper → 2D CAD → 3D CAD
- Vectors and curves drawn in 2D space
- Extend 2D → 3D with the help of commands such as EXTRUDE and REVOLVE
- Faces give the appearance, but not a real simulation, of solid objects.



\* No real standard term for this

# “NeoClassic” CAD Example: Sketchup

- Built around relatively small # of intuitive tools
- Active community, huge library of plugins
- “Solid” tools give you some solid-modeling-like commands
- Vector-based geometry: no true curves
- .STL export requires plugin, and can be buggy.
- Free non-commercial version available. Pro version \$695

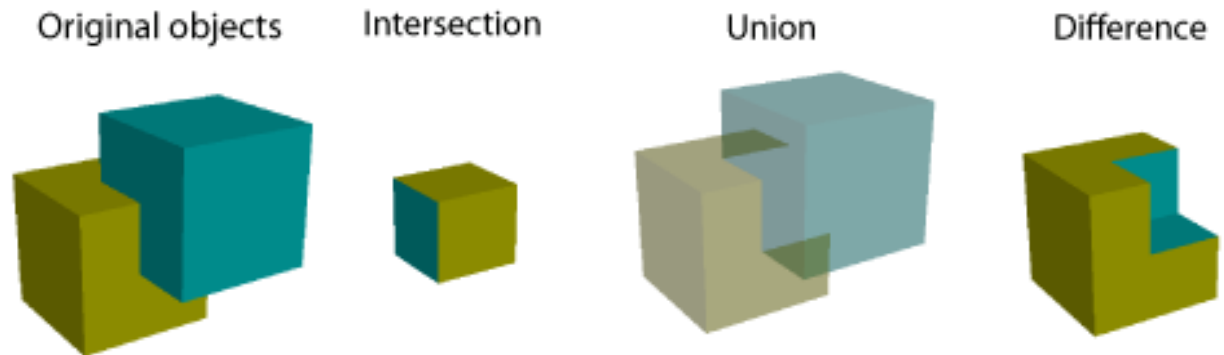




# Constructive Solid Geometry

- Based around solid volumes, rather than faces
- Combine mathematical “primitives” like cubes, spheres and cylinders using Booleans.

- Union
- Difference
- Intersection



- Ordered modelling: original primitives remain part of file structure, can be modified later
- Full-featured programs expand from here, + CAE

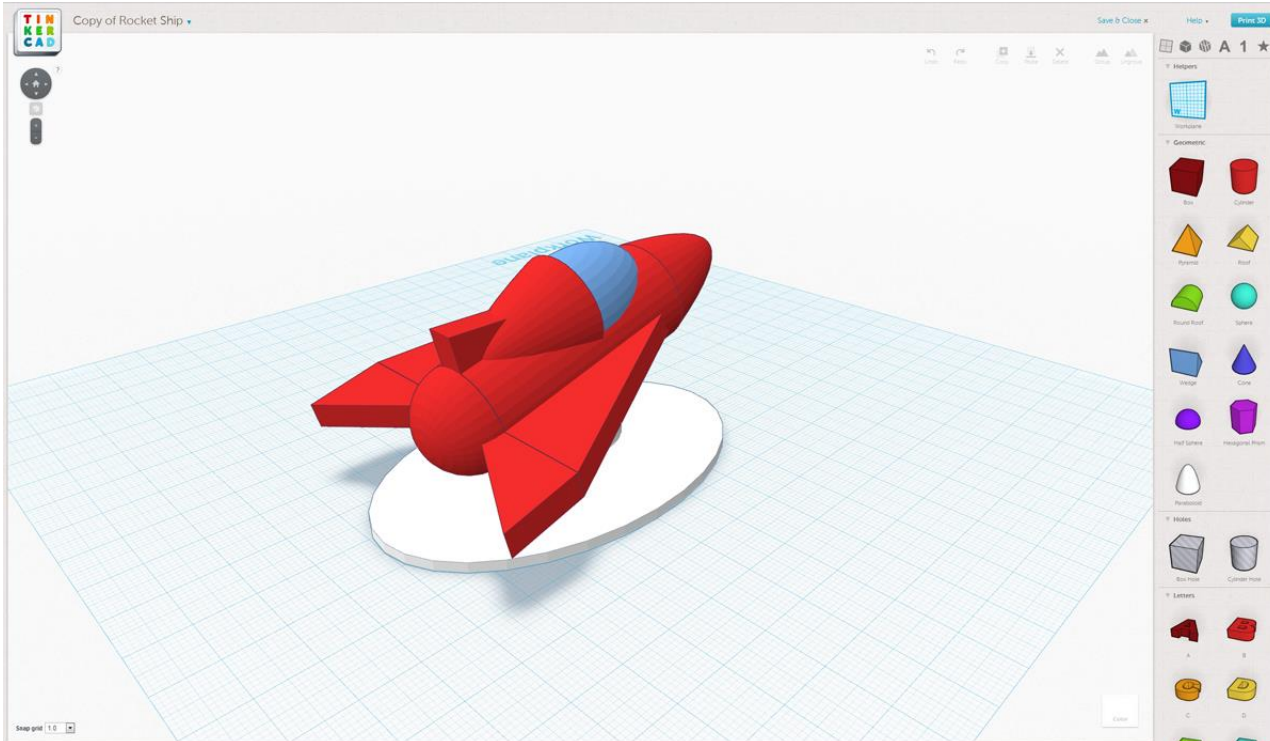


# CSG quick note...

- Most 3D modelling and CAD platforms incorporate Boolean commands in some form
- Only in CSG do they make up the core of the 3D file structure and work flow
- Booleans in different file formats:
  - CSG solids: robust and fast
  - BREP solids: good, but somewhat less robust/fast
  - 3D drafting models: must be manifold, can be buggy
  - Polymeshes: OK for simple stuff, slow and frustrating for complex models

# “Fake” CSG: TinkerCAD

- Polymesh-based under the hood, but uses simple CSG/Boolean workflow
- Easy to learn, just drag and drop shapes.
- Free, **Completely browser based**.
- Can import from large library of things made by other users
- Great for getting started, but lacks a lot of tools
- Polygon-based = no true curves

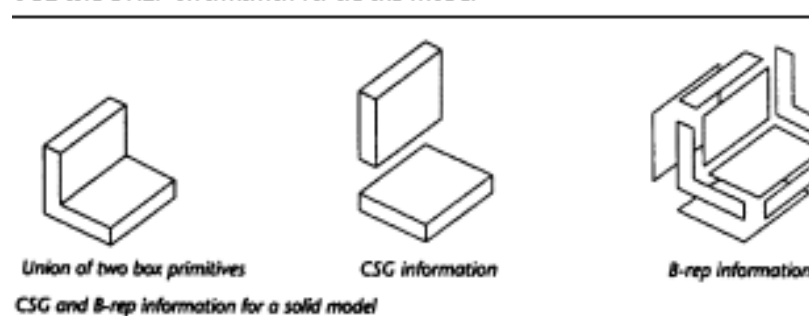


# Feature-Based Direct CAD

- AKA “Direct Solid Modelling,” “Direct BREP CAD”...
- Solid objects are defined as the space bounded by a set of faces/surfaces
  - Boundary representation = BREP
  - Similar to a manifold drafting model, but it’s a simulated solid, not just a surface shell

**Figure 2**

CSG and BREP information for a solid model

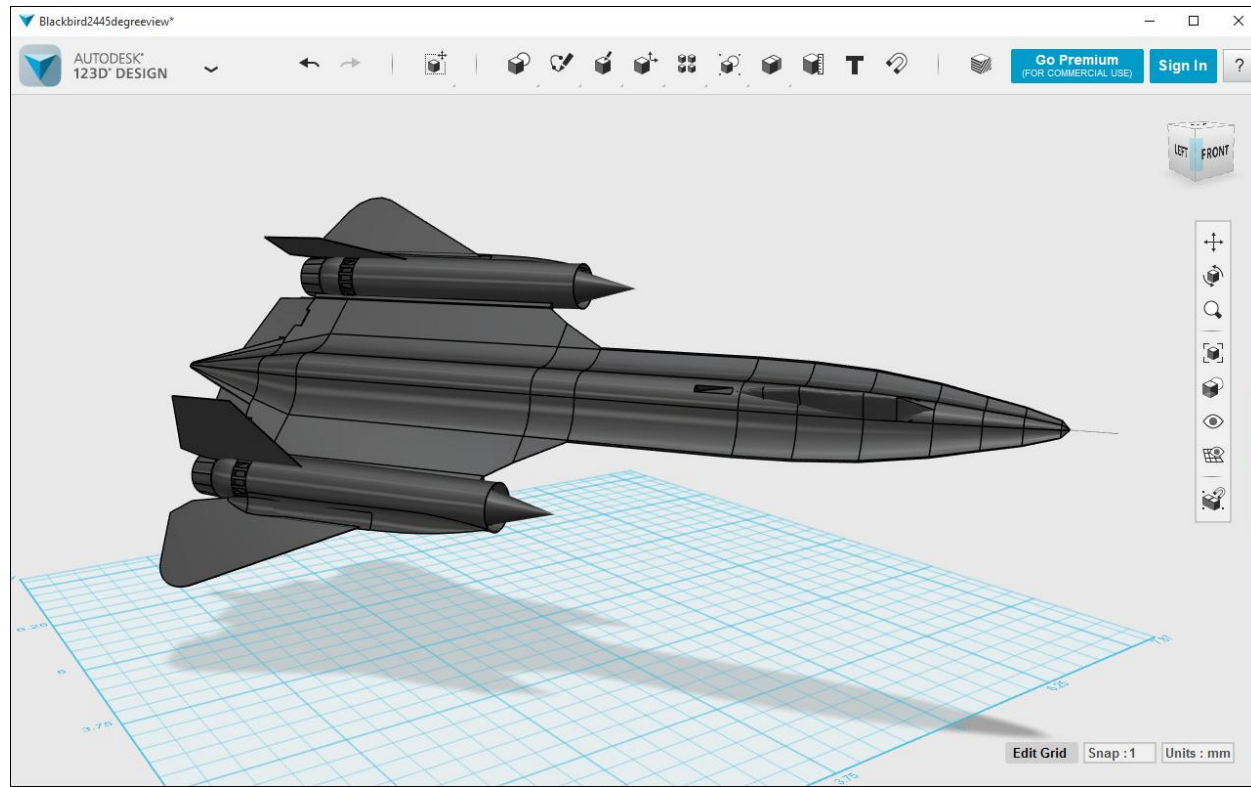


- Models are created using variety of “features”:
  - Sketch objects that are extruded, revolved, etc
  - Geometric primitives combined with Boolean commands
  - Modifications such as fillets (rounded corners), holes, etc

# Feature-Based Direct Modeling Example:

## 123D Design

- Basic but functional solid modeling
- Tries to be intuitive (IMO harder than Tinkercad, on par with Sketchup)
- Part of the AutoCad 123D Suite (free for non-commercial, \$10/mo commercial)
- Interface very similar to Inventor and Fusion 360



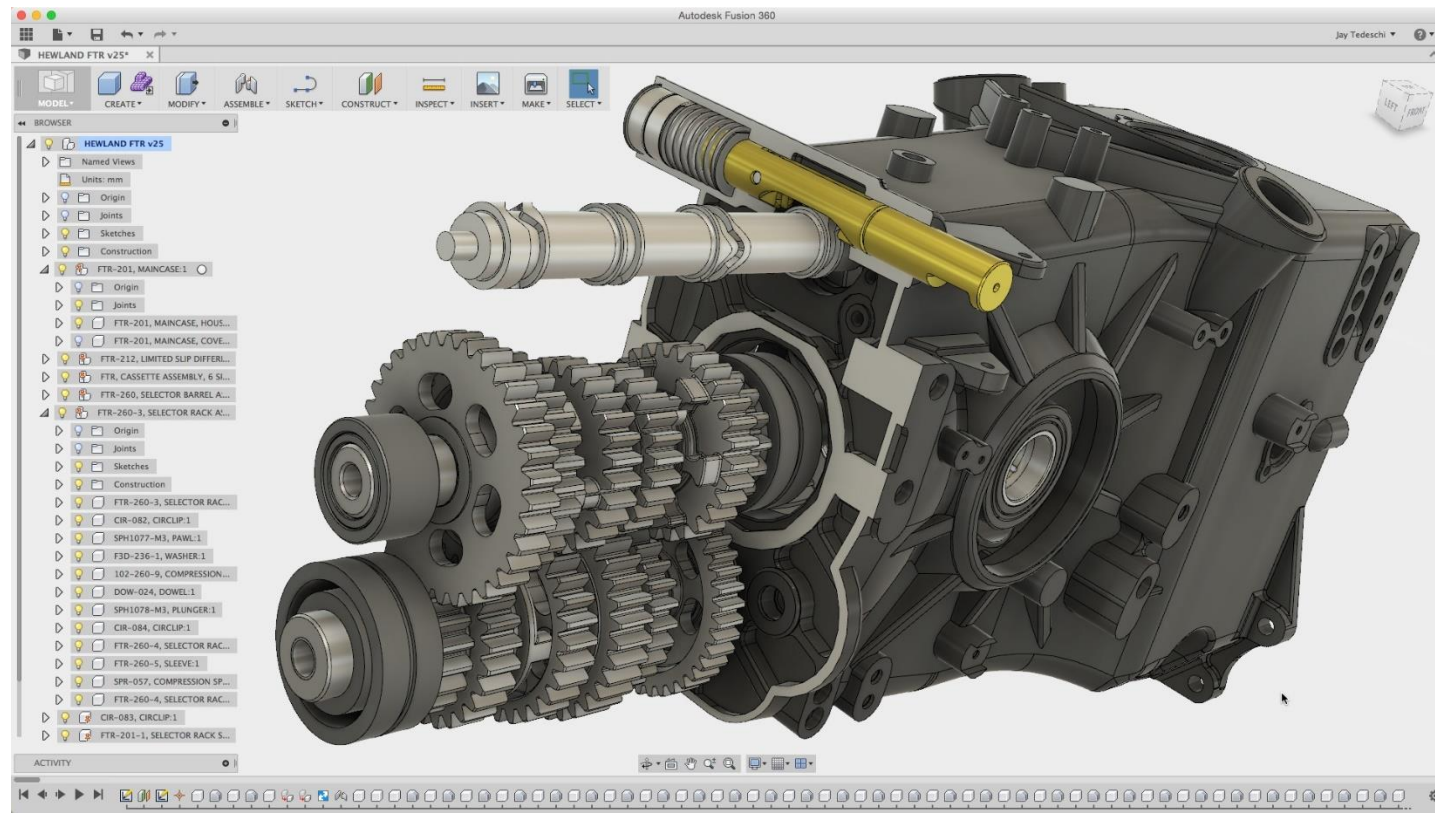
# Feature-Based Ordered CAD

- AKA: “Parametric Solid CAD,” “History-based BREP Modeling”, etc...
- Similar to feature-based direct: BREP solids are created from a variety of features (sketch, extrusion, solid primitives, fillets, etc).
- Every feature becomes part of the model **history**, and can be returned to and edited later
- Every defined length, angle, etc becomes a **parameter** which can be edited in table form, and can be defined by equations referencing other parameters.

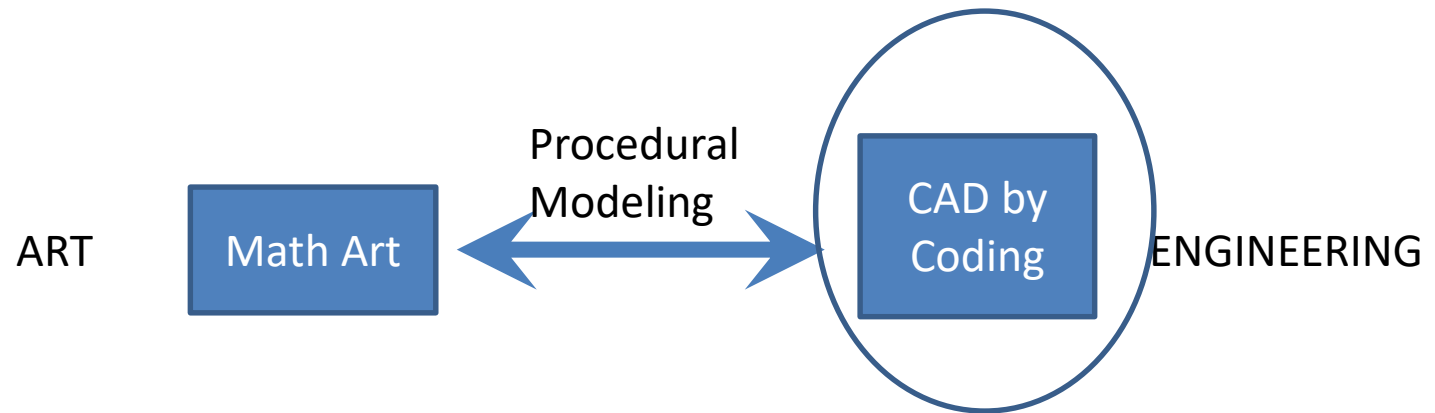


# Feature-Based Ordered Example: Fusion 360

- Fully functional parametric CAD, free for DIY and “startups” making <\$100K/year
- Autodesk’s attempt to do everything in 1 program. Also has: Direct CAD mode, freeform splines, CAM, collaboration tools, and even a little polymesh editing.
- Designed to be used with cloud connection (offline mode somewhat crippled)...you are at their mercy as it gets updated.
- Not much CAE compared to pricier software



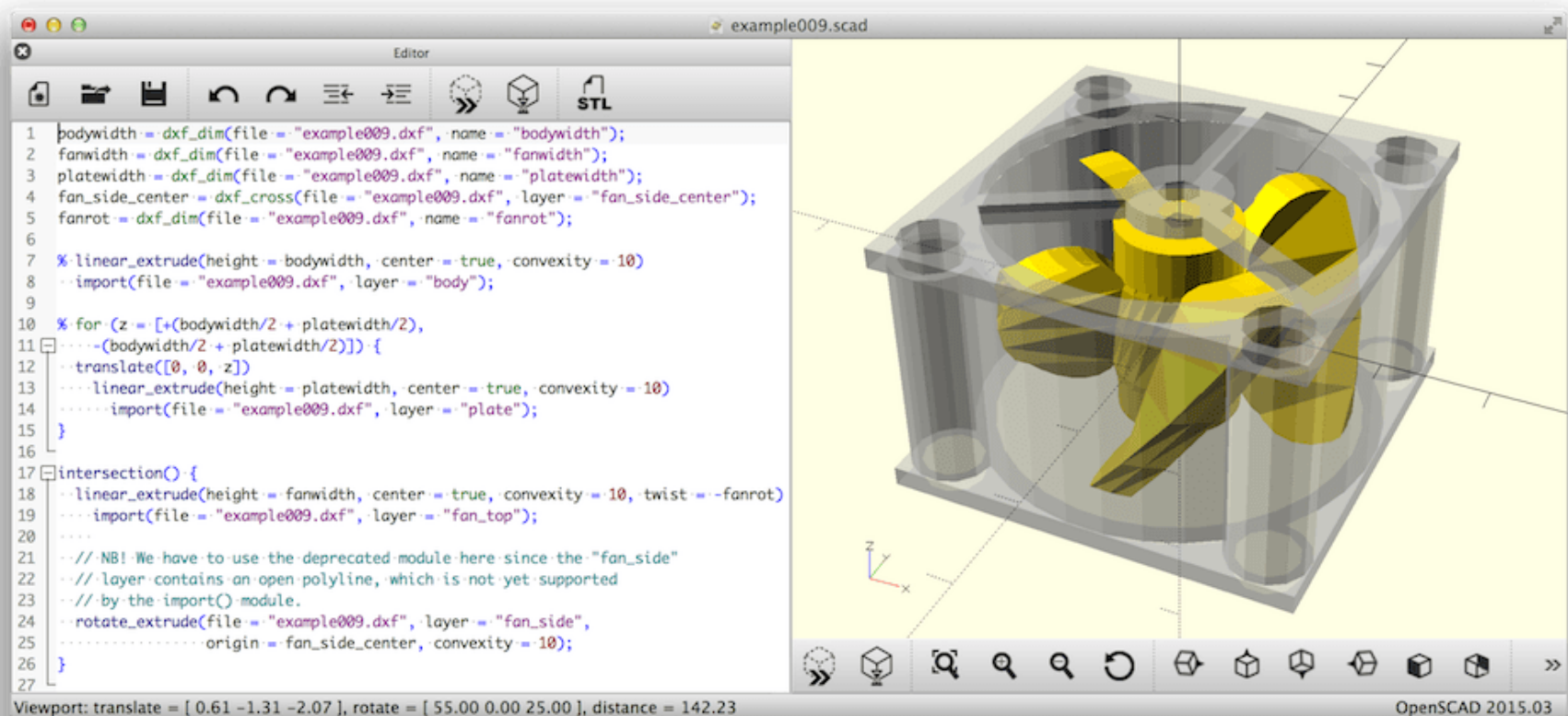




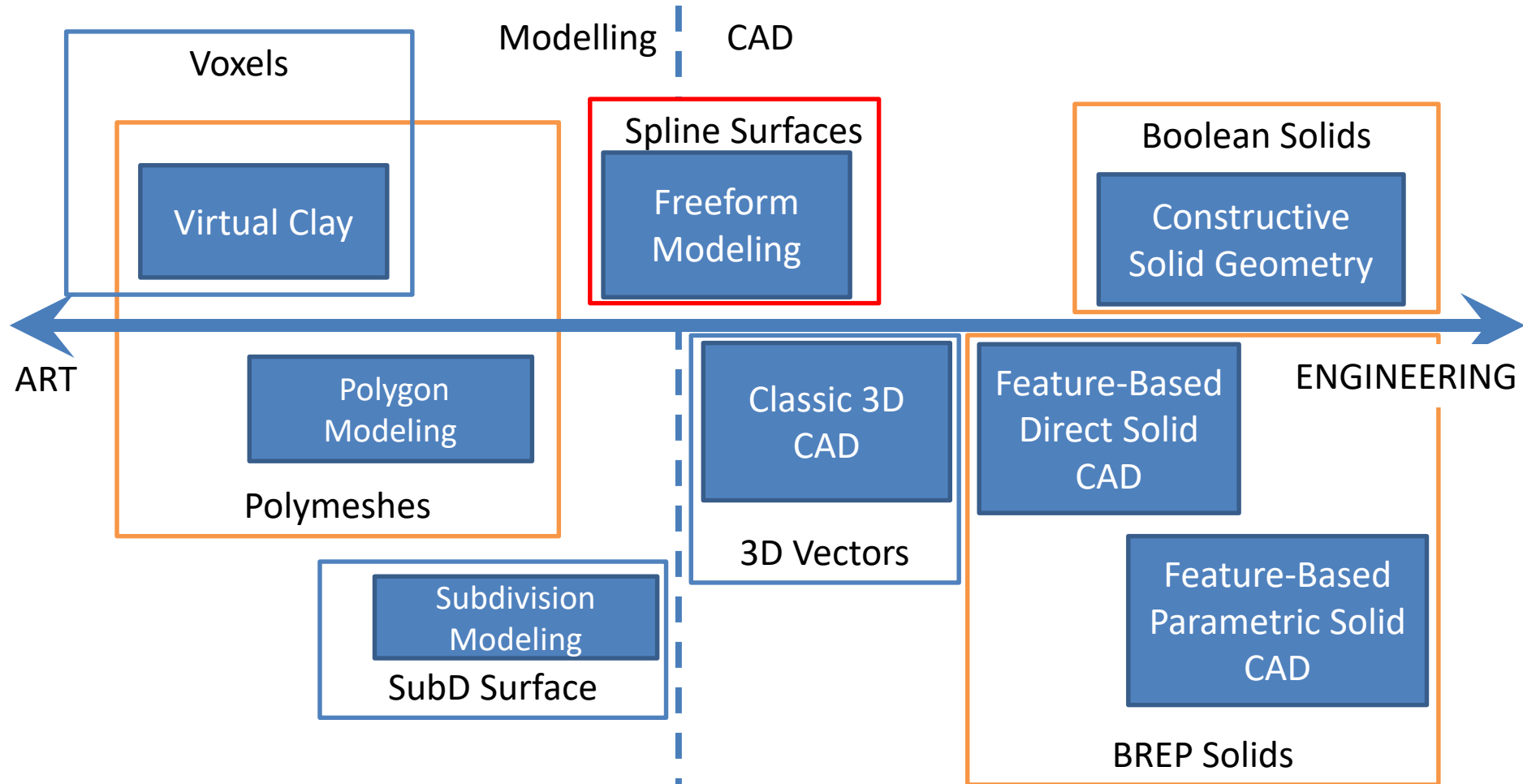


# CAD by Coding: OpenSCAD

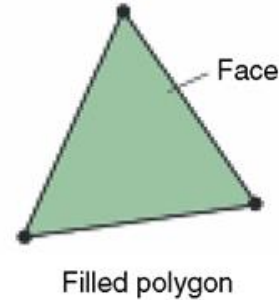
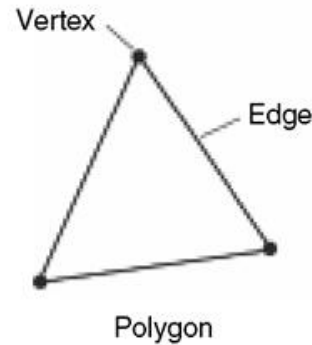
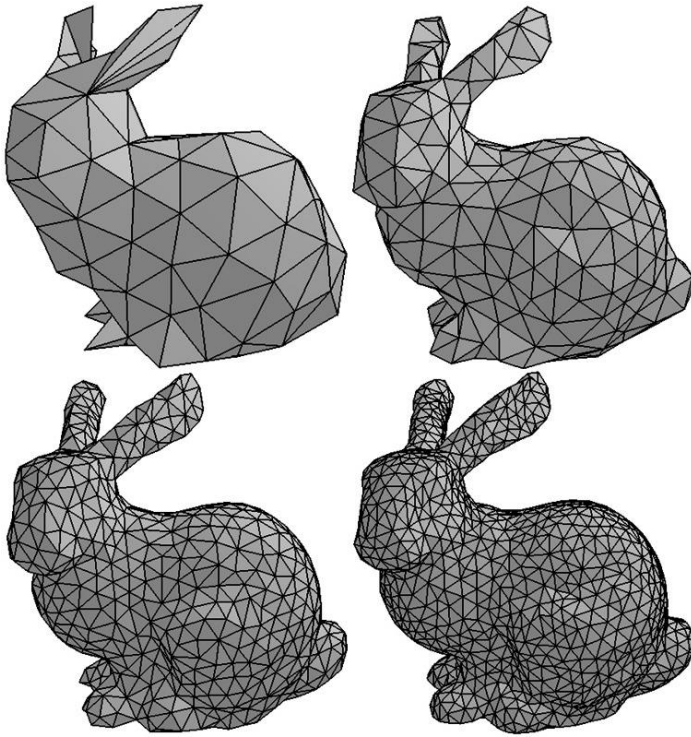
- Analogous to parametric ordered modelling, but everything is done by lines of code rather than interacting with the object directly
- Intuitive for coders...non-intuitive for non-coders
- Nice for making simple customizable objects
- Can import STL's and use Boolean combos with code-generated features
- IMO, cumbersome to plan and code complex objects



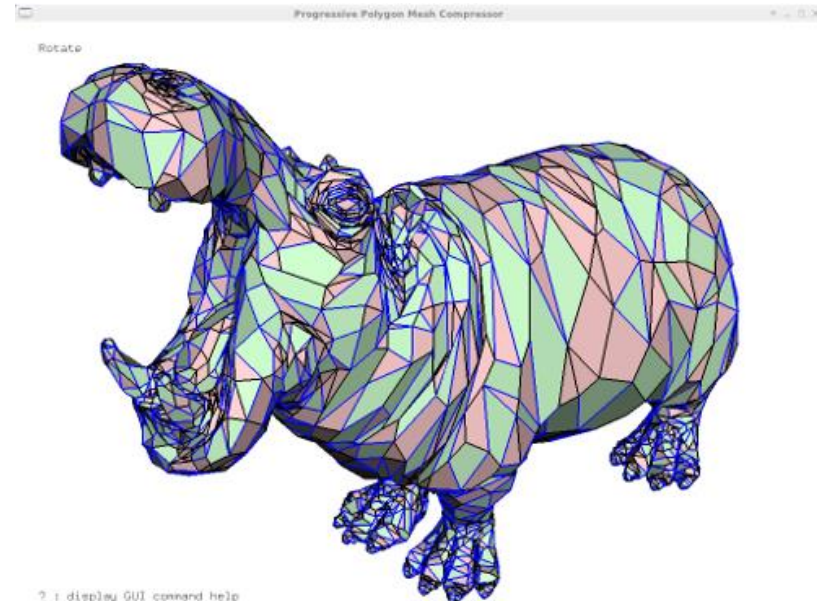
# Different Tools for Different Needs



# Mesh (Polymesh, Polygon Mesh)

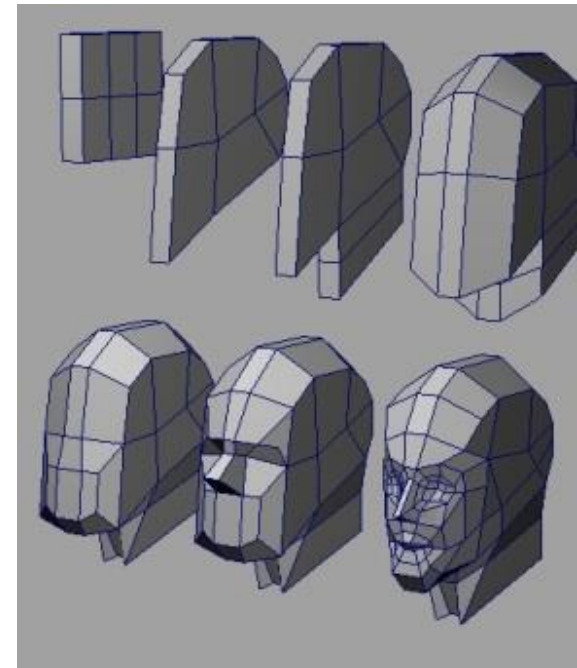
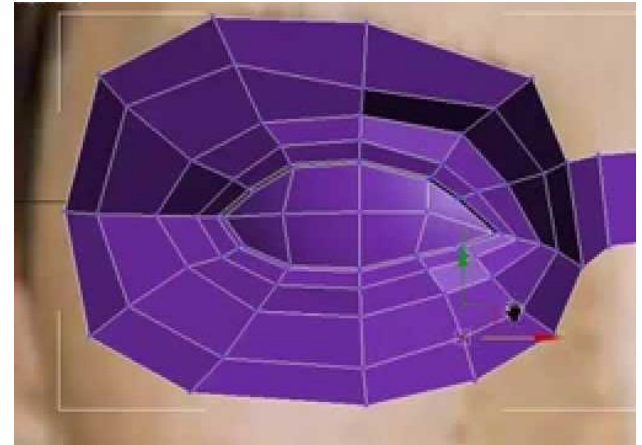


- Shapes defined by a set of polygon faces
  - NOT a solid.
- More poly's = more detail, larger file size
- Common file flavors:
  - All triangles (tri's)
  - Mixed polygons (tri's, quads, n-gons)
  - With or without surface colored



# Polygon Modelling

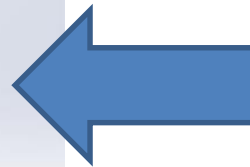
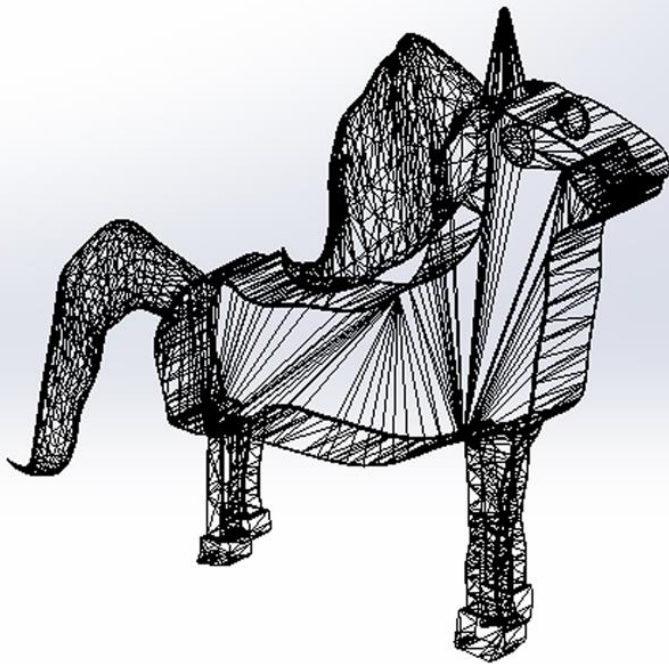
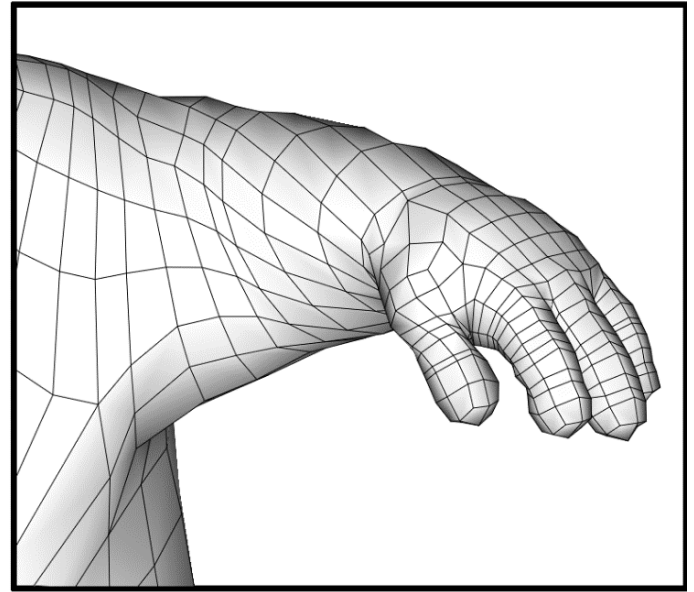
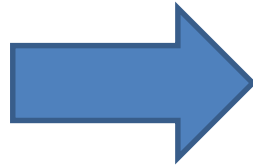
- Multiple techniques to create a polygon mesh...
  - Boolean combos of polygon primitives
    - Gets slower and buggier as file gets more complex
  - Edge modelling
    - Draw the edges of each polygon
    - **complete control**, but very time consuming
    - Useful to trace a background image
  - Box modelling
    - Start with a cube or other primitive
    - extrude and divide faces into smaller faces
    - move vertexes, tweak edges, etc.





# Mesh Topology

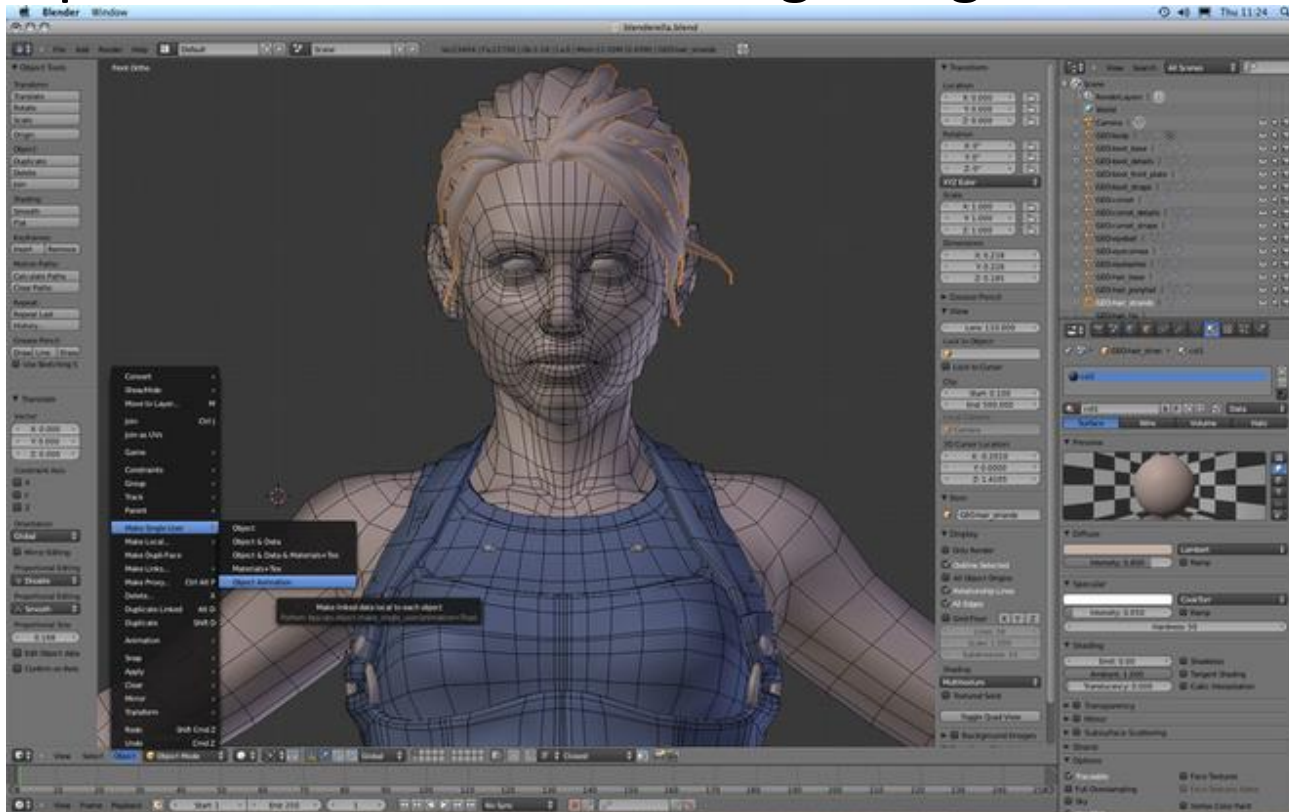
“Mostly quads” topology is best for bending, posing, animation, and for conversion to Freeform and SubD file formats



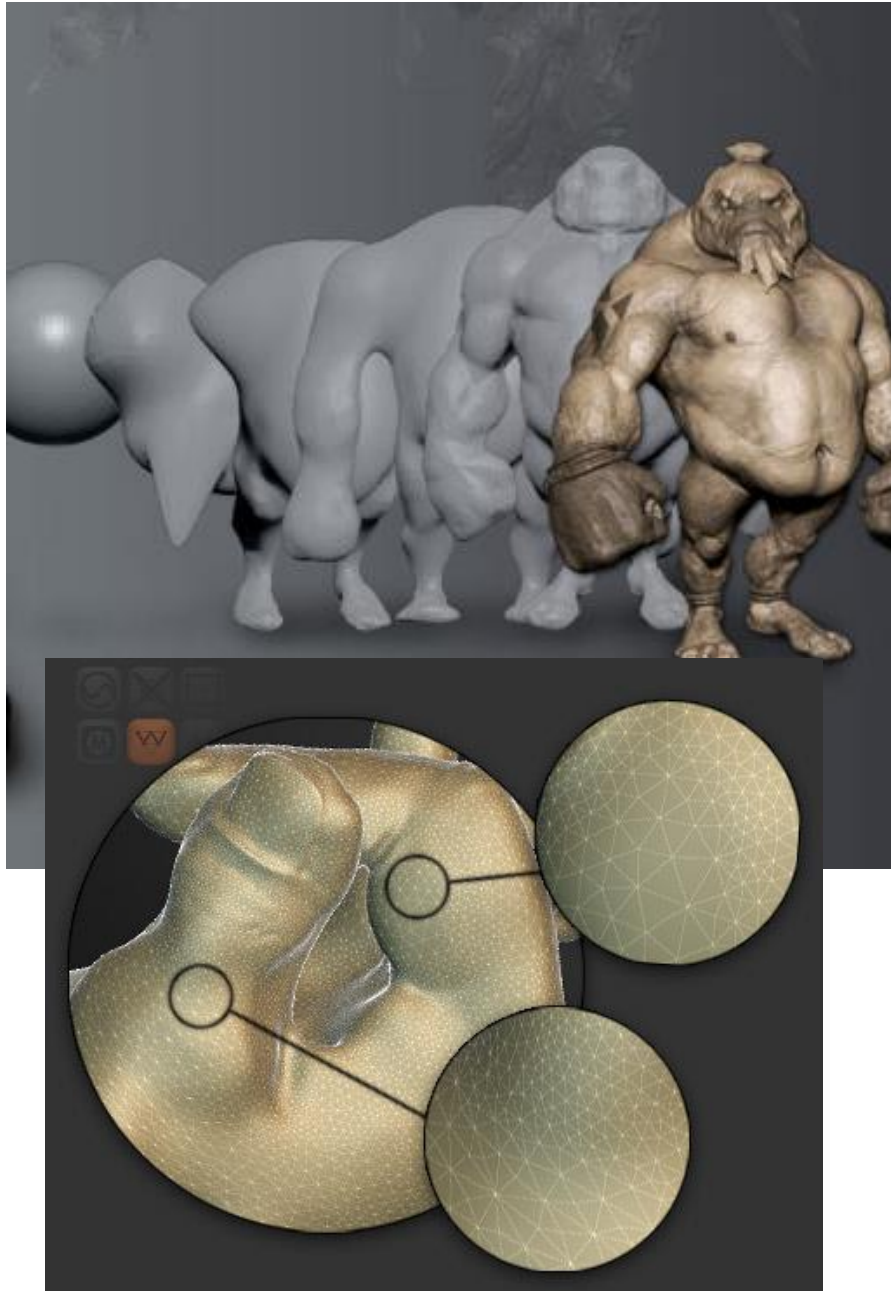
.STL export from a CAD program usually gives you lots of skinny triangles. This will be miserable to try to edit in a polygon modeler (use a remesh tool first)

# Polygon Modelling Example: Blender

- One of the most powerful pieces of free open-source software out there
- Tools for **polygon modeling**, freeform modeling, subdivision modelling, sculpting, and animation.
- Active, helpful community. Many plugins.
- Complex user interface takes getting used to...



# Digital Clay

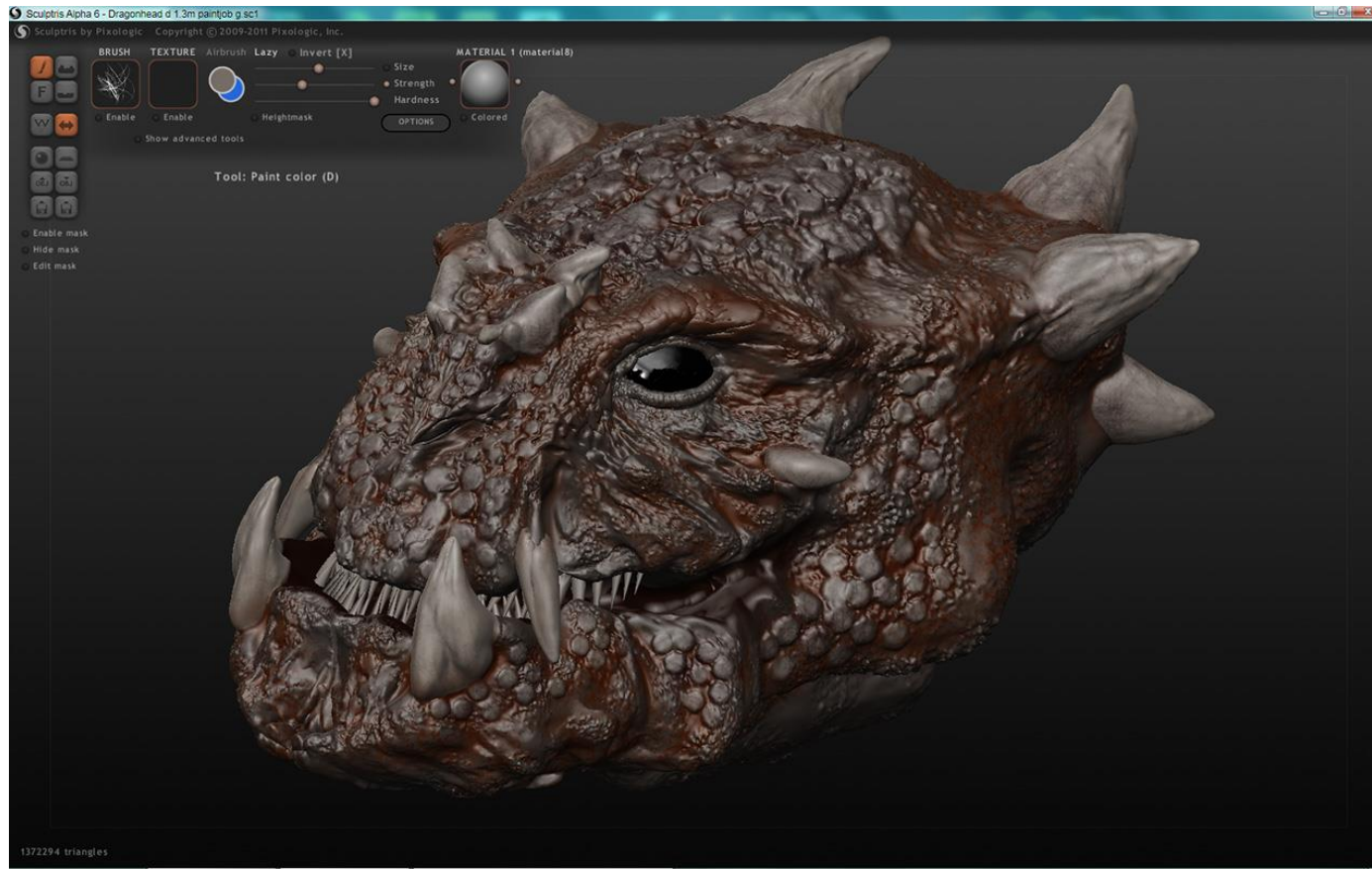


- AKA digital sculpting
- Use tools on a virtual ball of clay to draw, inflate, drag, carve, etc
- Most software is based on polymesh; also some voxel-based examples.
- For triangle meshes, can turn on or off Dynamic topology
  - additional tri's are generated as needed to create higher level of detail
- Can be used with mouse, 2D stylus pad or 3D haptic feedback stylus



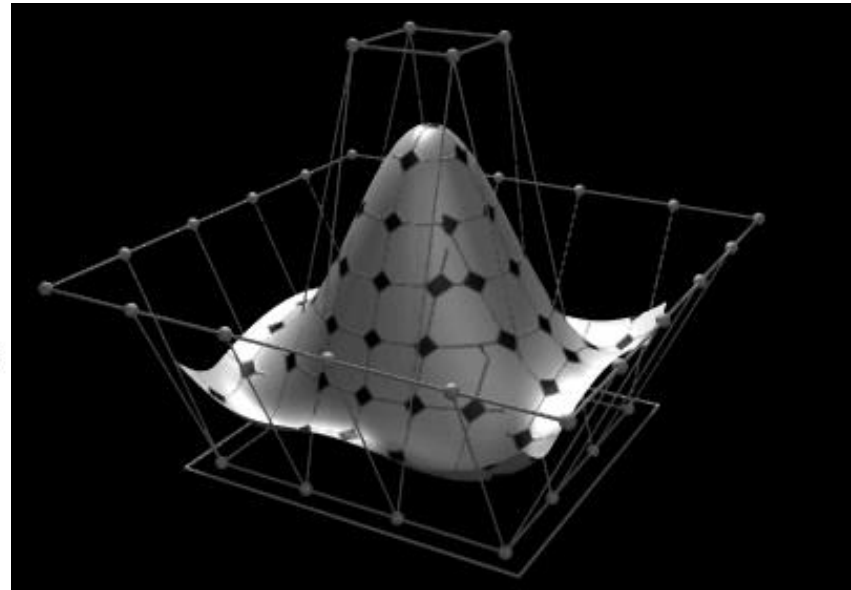
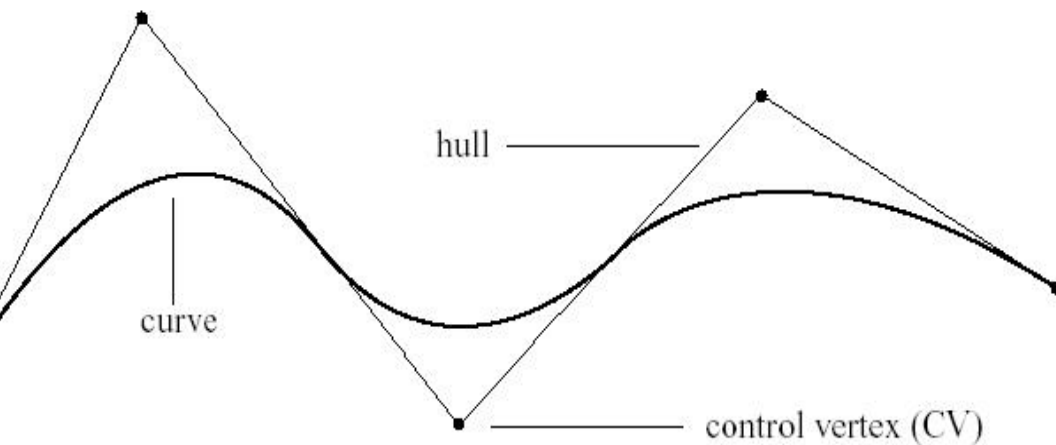
# Digital Clay Example: Sculptris

- easy to jump in
- Free little sib of Zbrush (\$\$\$ sculpting tool)



# Freeform Modelling

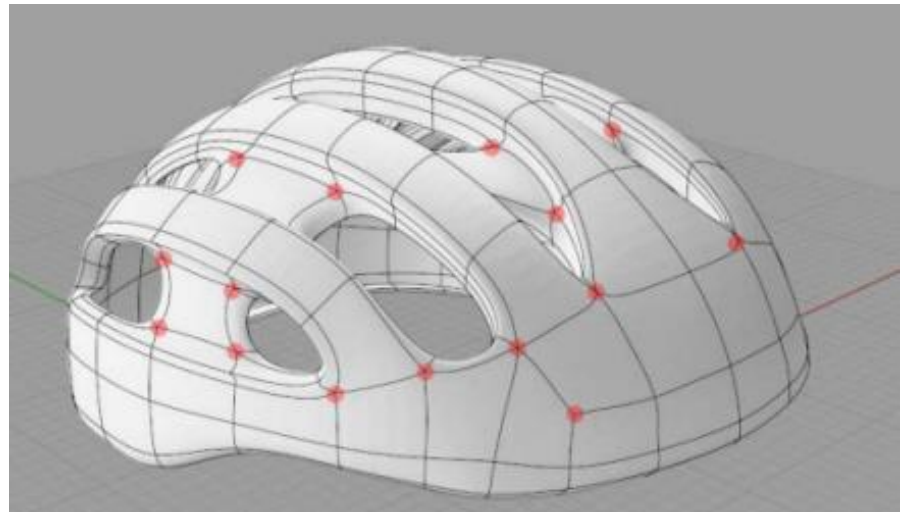
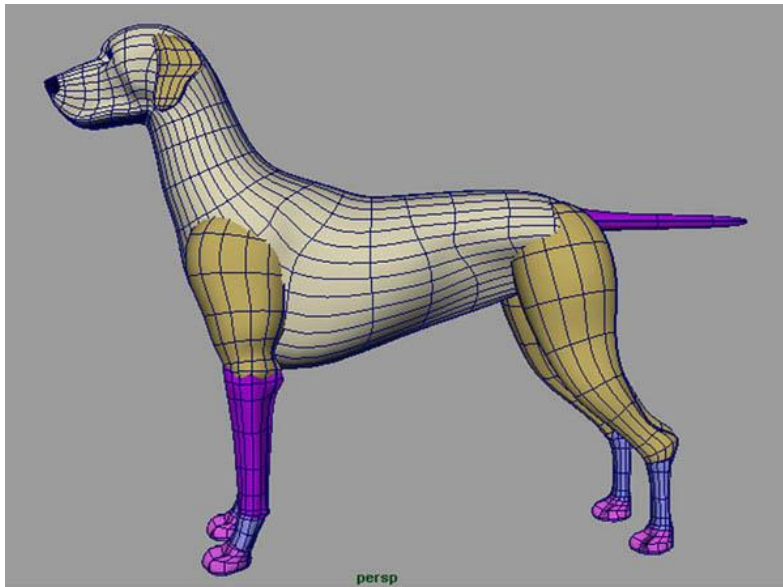
- AKA: Spline modeling, surface modelling
- Model is created by a lattice of splines



- Start with a spline primitive such as plane, box, or tube
- Edit the form either by moving control points or using tools that “sculpt” the surface directly

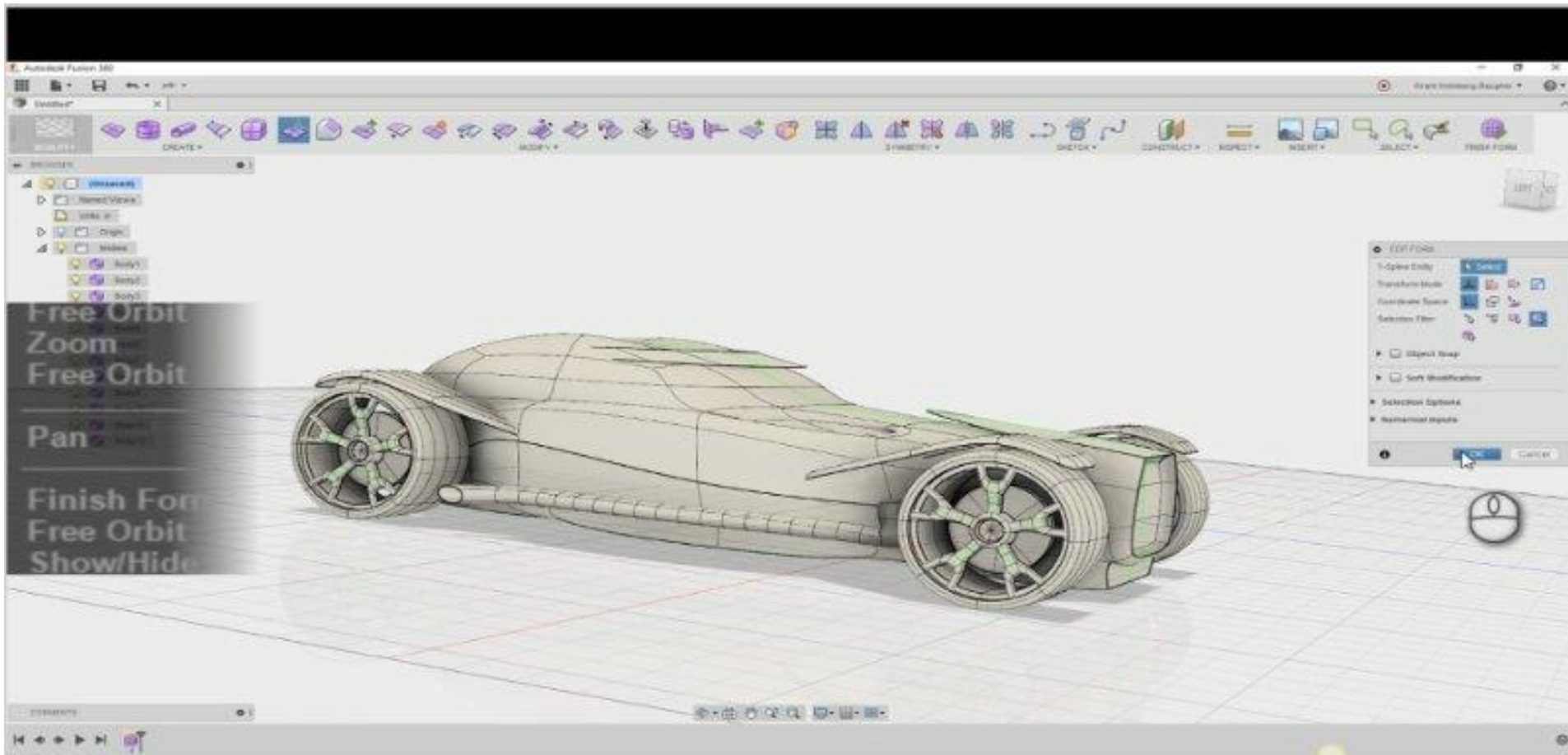
# Freeform Modelling--Flavors

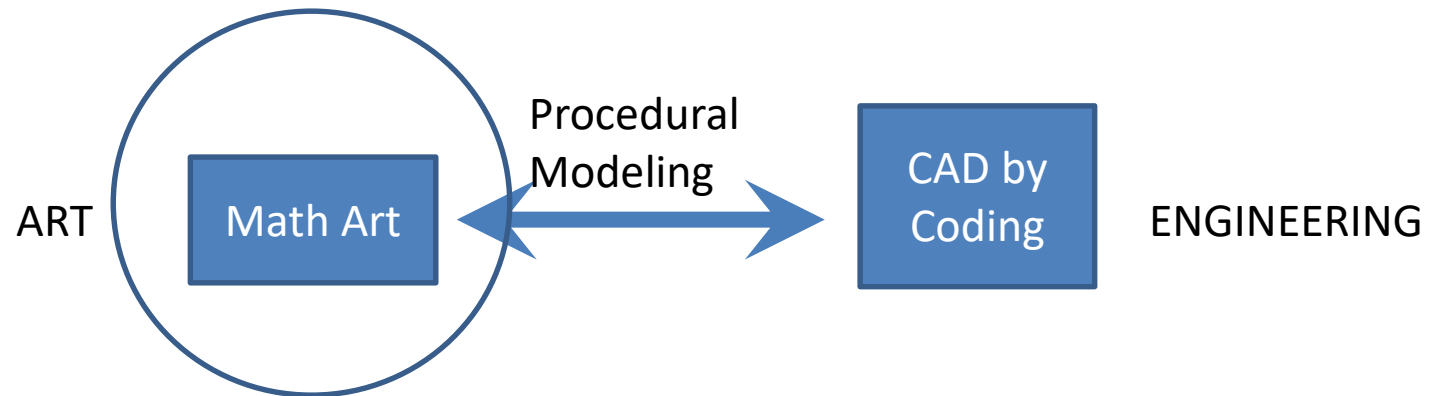
- NURBS (non-uniform rational B-splines)
  - Original and still very common for freeform modelling
  - Spline curves must form a quadrilateral grid
  - For complex shapes, multiple patches stitched together
- T-splines
  - Like NURBS but can terminate at T's and star-points
  - Allows you to create complex shapes without patches



# Freeform Modelling Example: Fusion 360

- The “sculpt” mode in Fusion 360 lets you create and edit T-splines.
- Can bring your T-spline form back into the “model” mode to combine it with feature-based BREPs

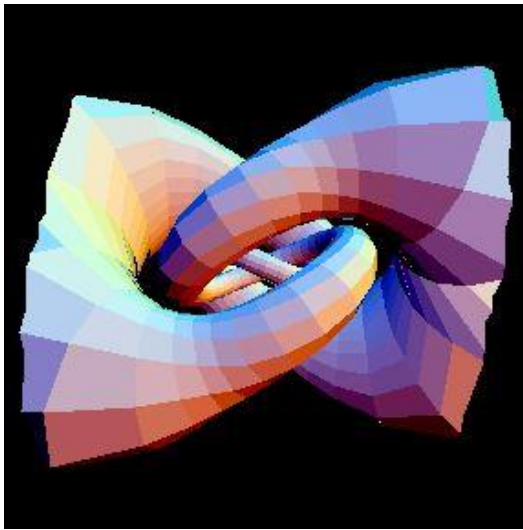






# Math Art

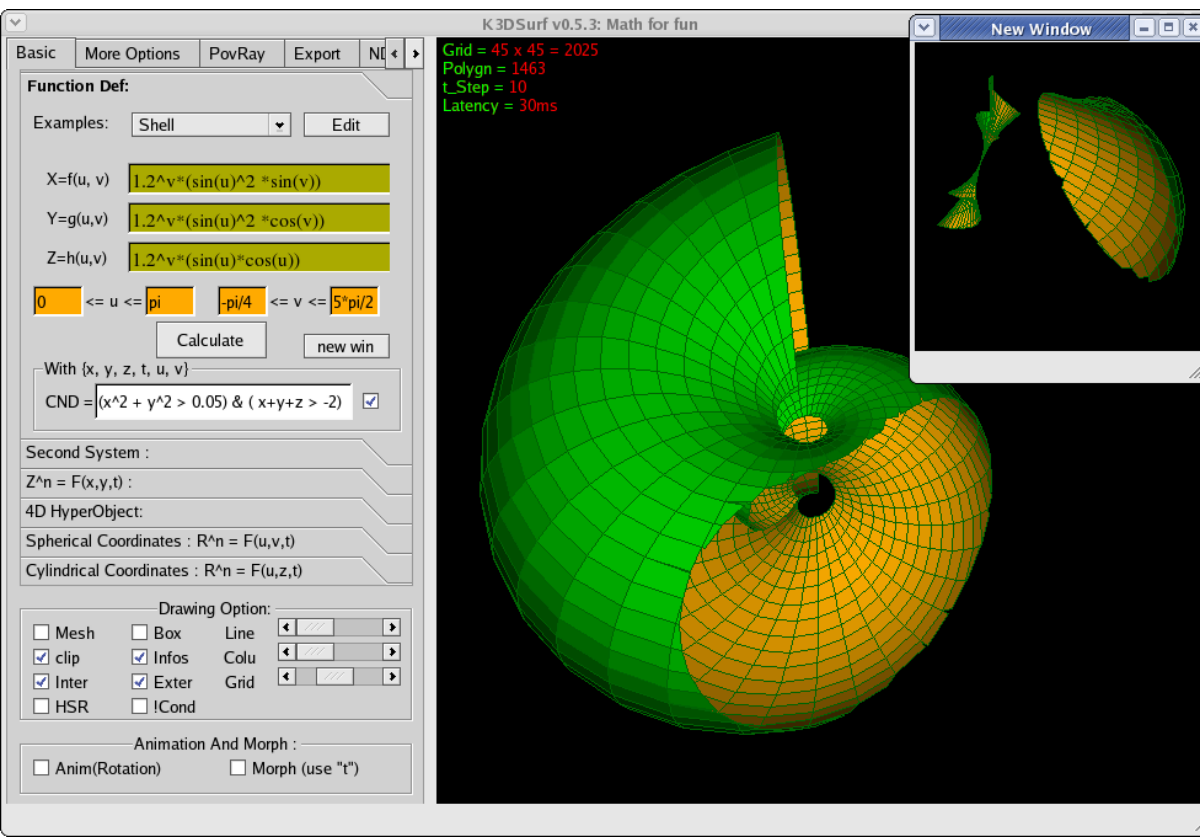
- I'm using this as a broad umbrella term:
  - Explicit and Implicit surfaces
  - 3D fractals
  - Procedurally generated art
  - artistic modification through filters
- Rather than creating a model “by hand”, you are creating a set of equations/parameters to generate a 3D shape
  - Complexity of process makes it difficult to predict exactly what you will get
  - Tweak the parameters, repeat until you get something you like
- Can be



# Math Art Example #1: K3DSurf

- Free, simple tool for creating implicit and explicit math surfaces. Exports polymeshes.
- Many examples included

GYROID  
 $\cos x \sin y + \cos y \sin z + \cos z \sin x = 0.$

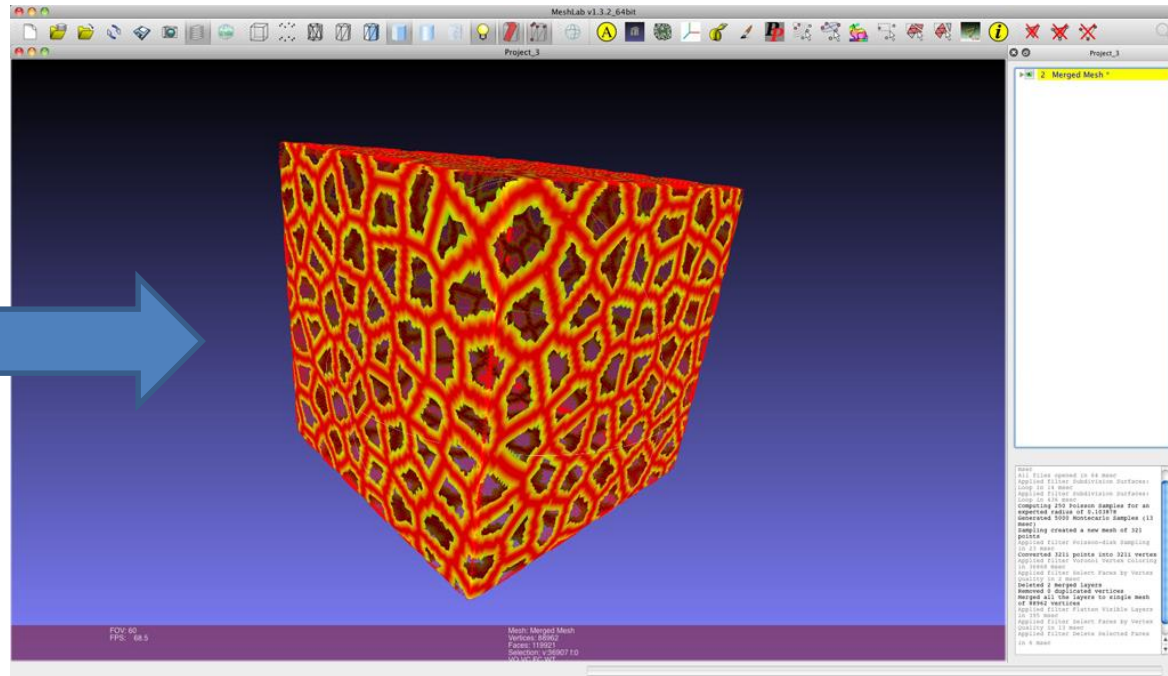




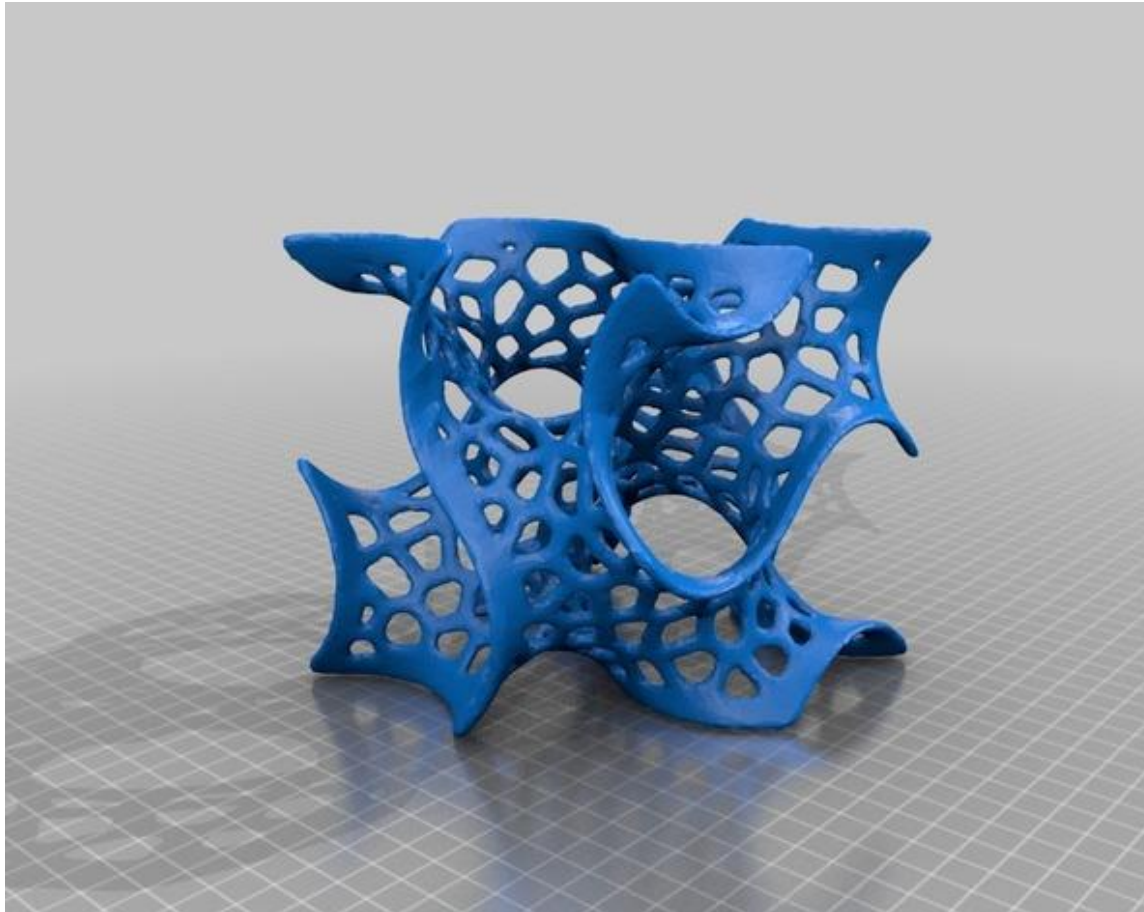
# Math Art Example #2: Meshlab

- Free, open source program; but not very user friendly.
- Can import and export many polymesh file types
- Big menus full of “filters,” algorithms that modify a mesh.
  - Fixing holes and other mesh problems
  - Increase or reduce polygon count
  - Smoothing, sampling, remeshing, and more

Voronoi  
sampling



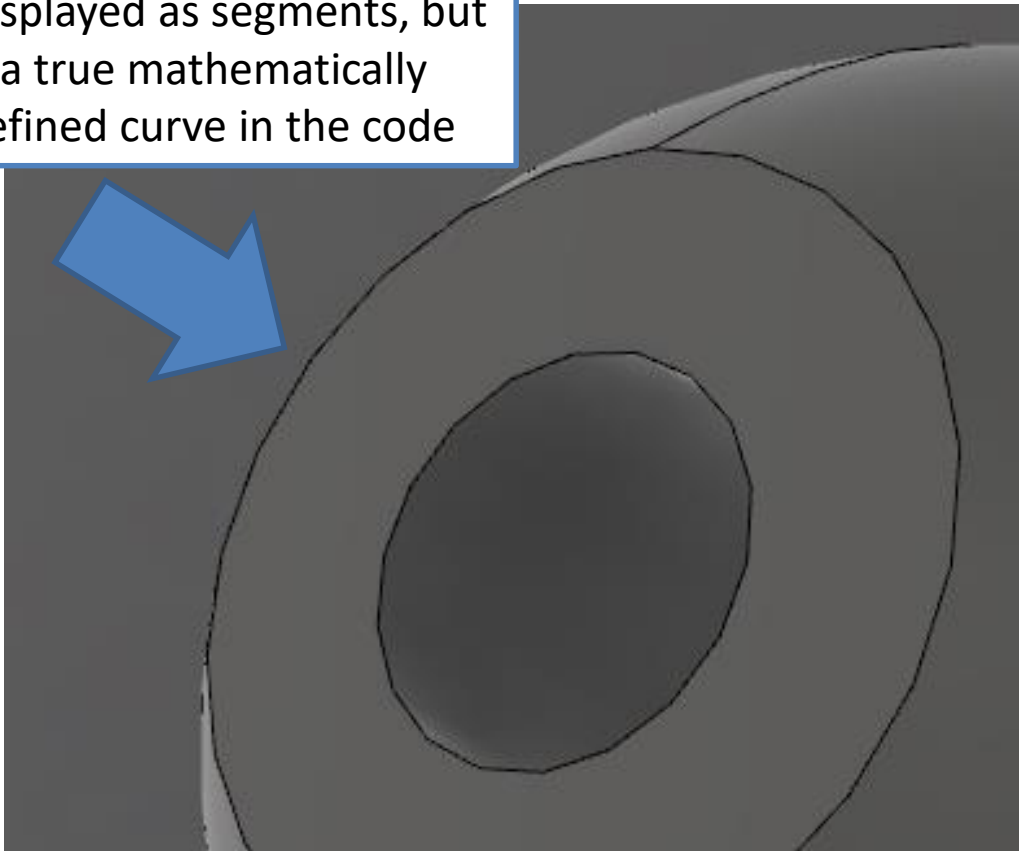
Gyroid + Voronoi Pattern = Gyrovoronoid



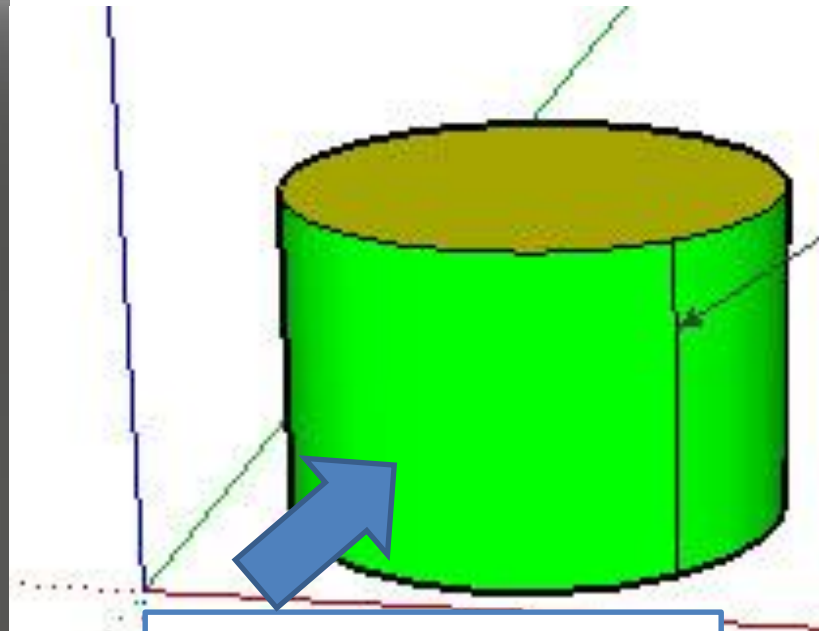
# Design Tips and Hints

# Understand how your program displays stuff; what you see not always what you get

Displayed as segments, but is a true mathematically defined curve in the code



Fusion 360



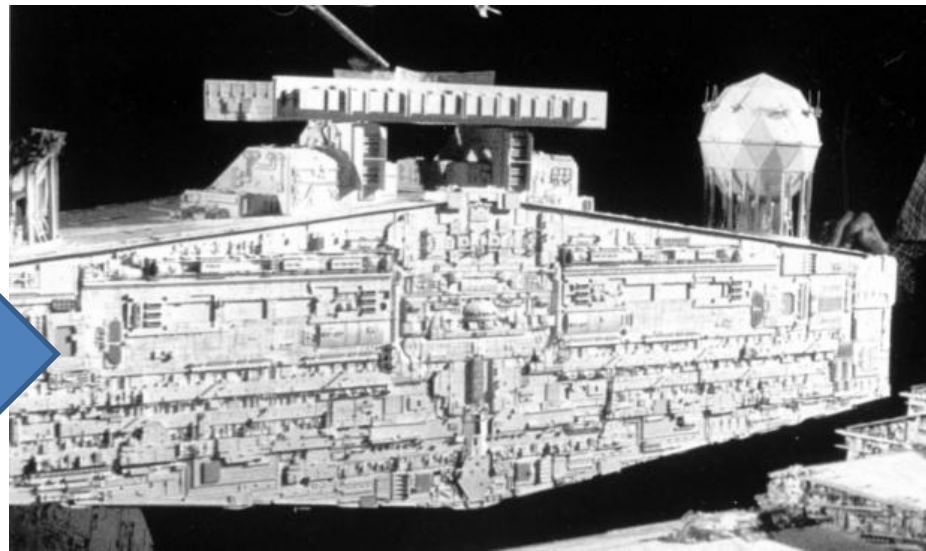
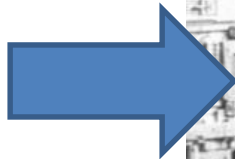
Looks smooth, but is really a group of many small flat faces in the code

Sketchup

# Use Kitbashing

- Originally referring to hacking hobby model kits: take kits apart, build something new

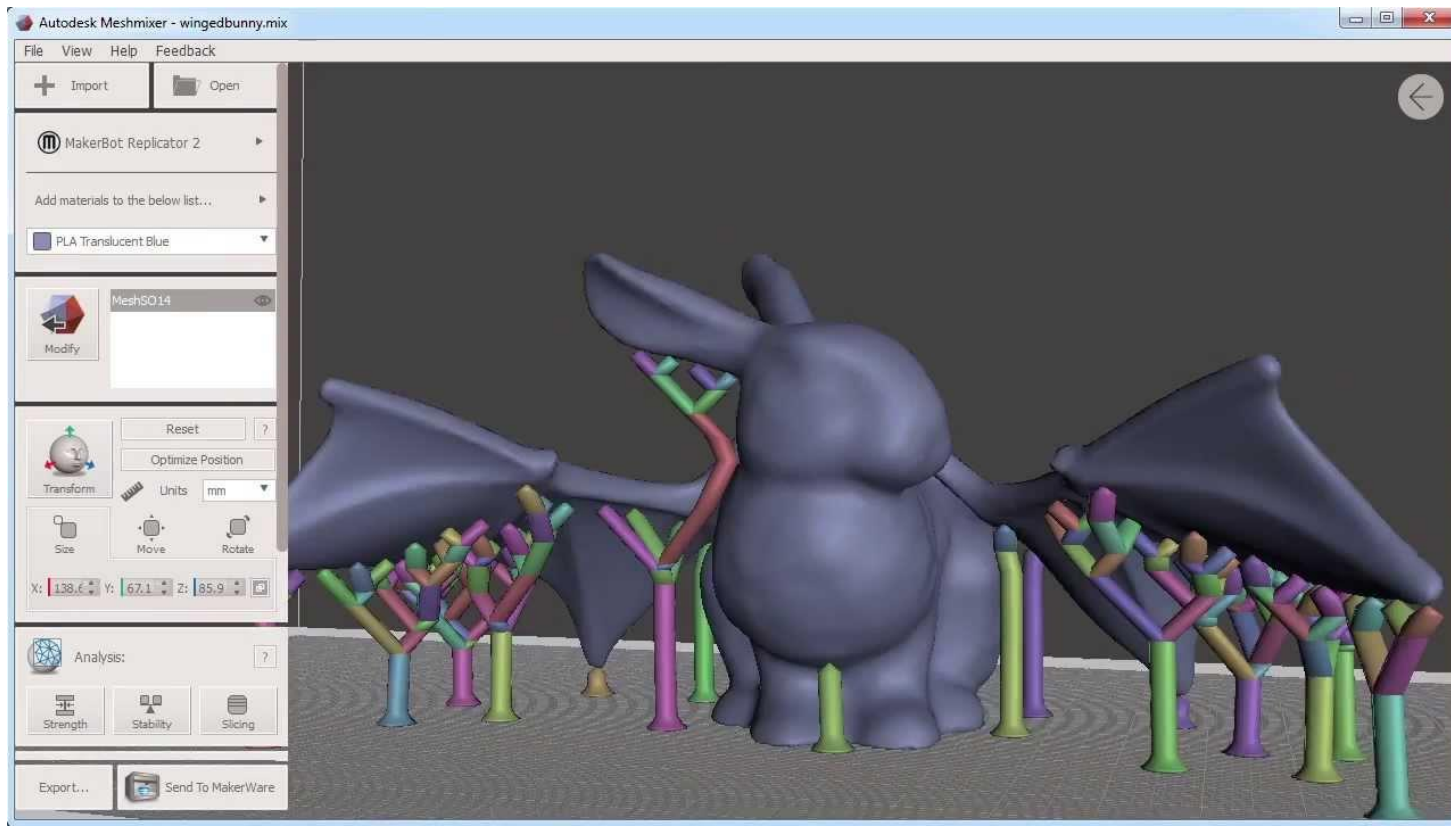
greebles



- Can do the same thing in 3D modelling and CAD! Many libraries of parts, free models, etc to draw from.

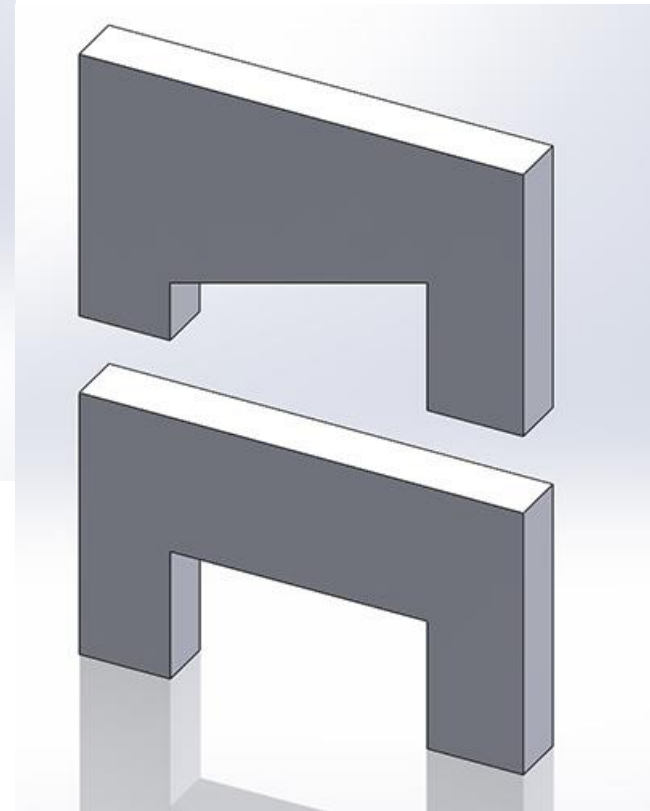
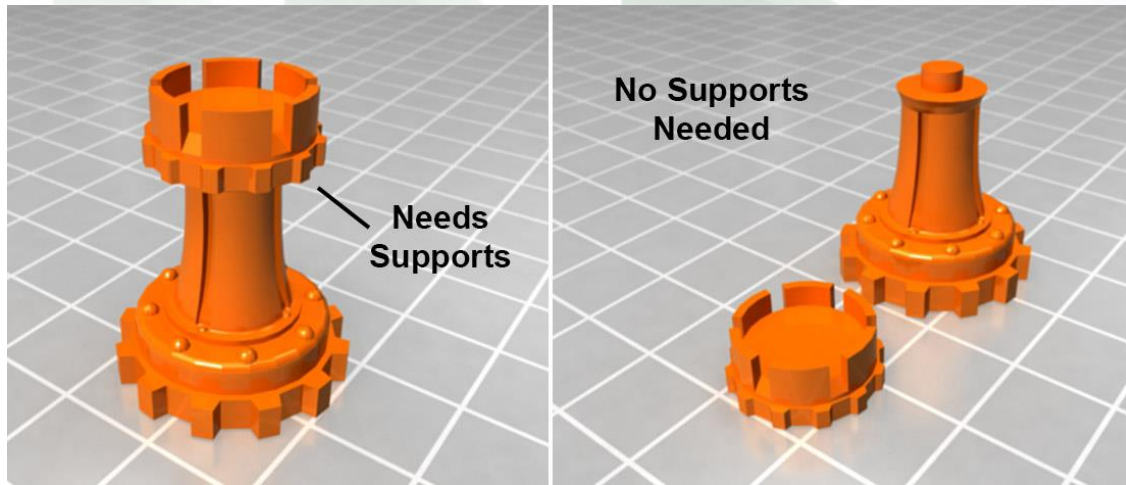
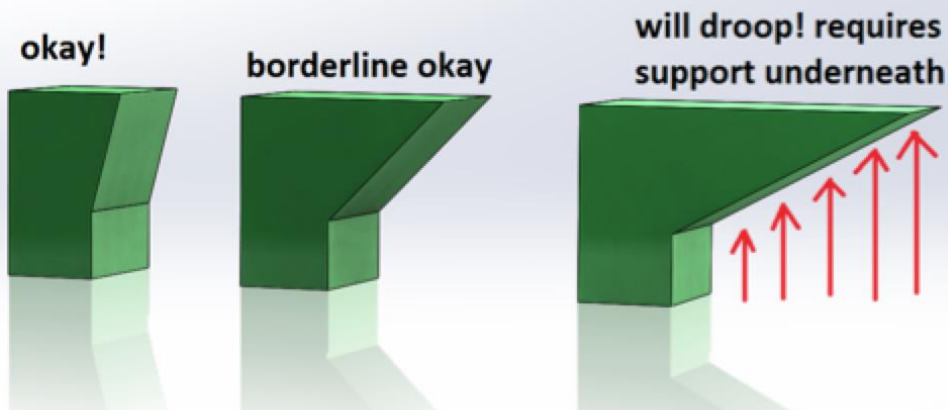
# Kitbashing Example: Meshmixer

- Free (but not open) program designed for the DIY 3D printing enthusiast
- Great for kitbashing polymeshes
- Also has sculpting, remeshing, support structure creation, and more
- Odd menu structure, features can be hard to find



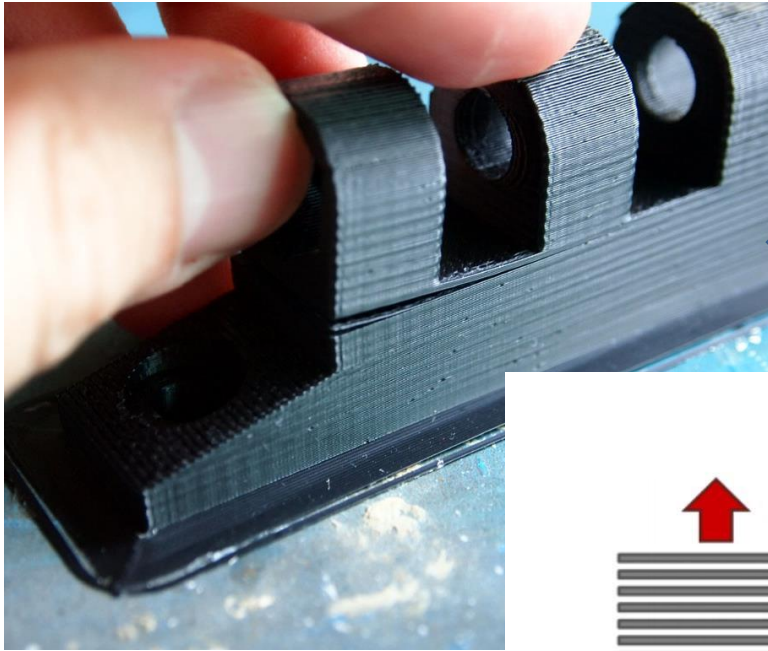


- Be aware of overhangs and need for support
  - Large curved overhangs especially difficult
  - May be easier to print in multiple pieces and glue

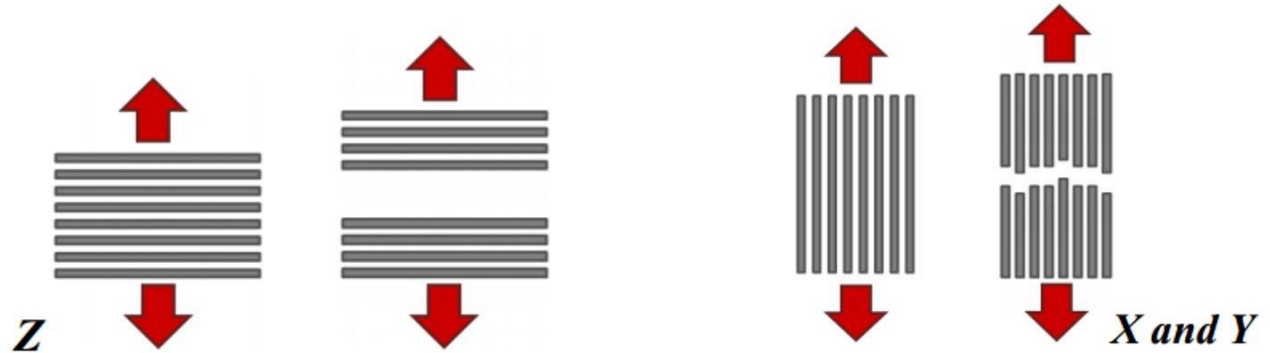




# Model Orientation Matters



FFF printed models are weak to Z axis force. Delamination of layers!

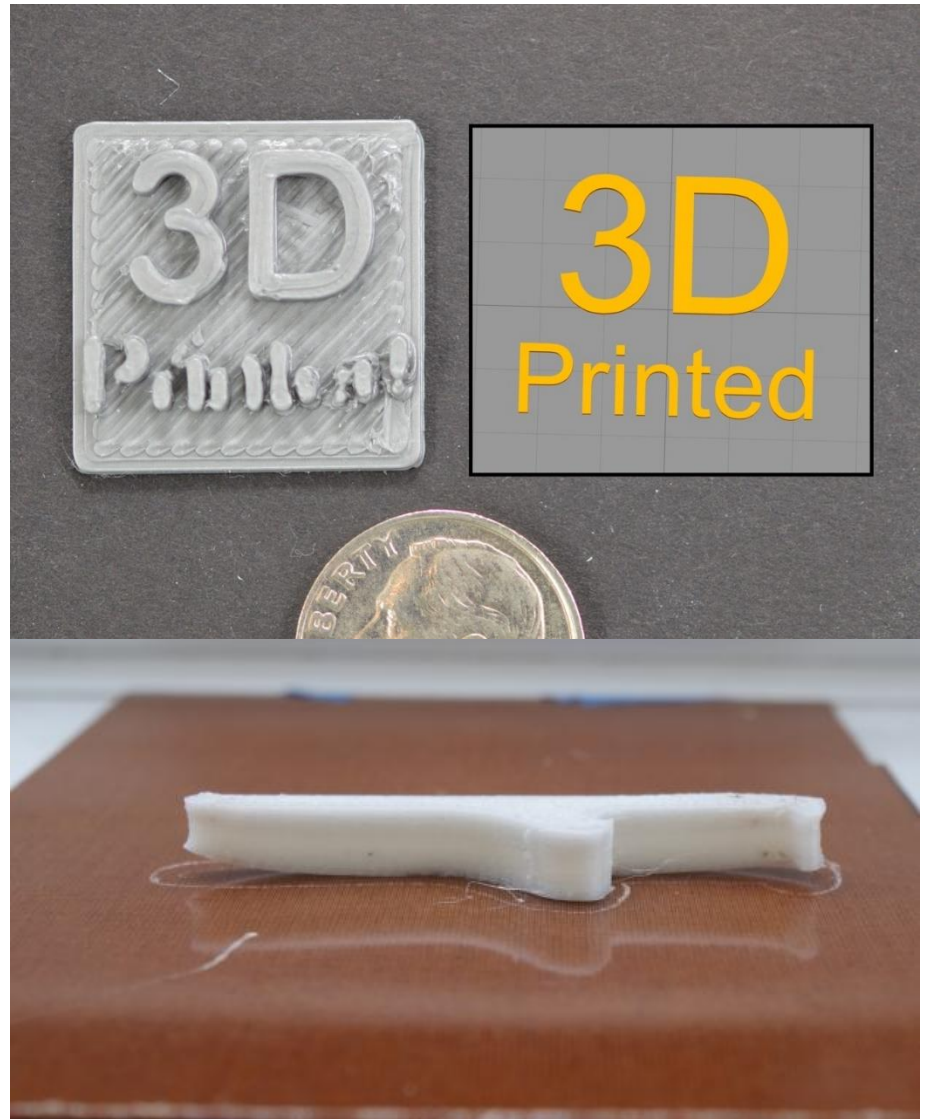


hard to achieve perfect vertical circles



# Know the limits of Desktop FFF

- Sloppy tolerances. I usually allow 0.1-0.2mm wiggle room.
- Details limited by layer height on Z axis, nozzle size on XY
- Plastic shrinks as it cools—may not stay dimensionally accurate, flat surfaces become curved.
  - Depends on plastic type
  - Common cause of print failure

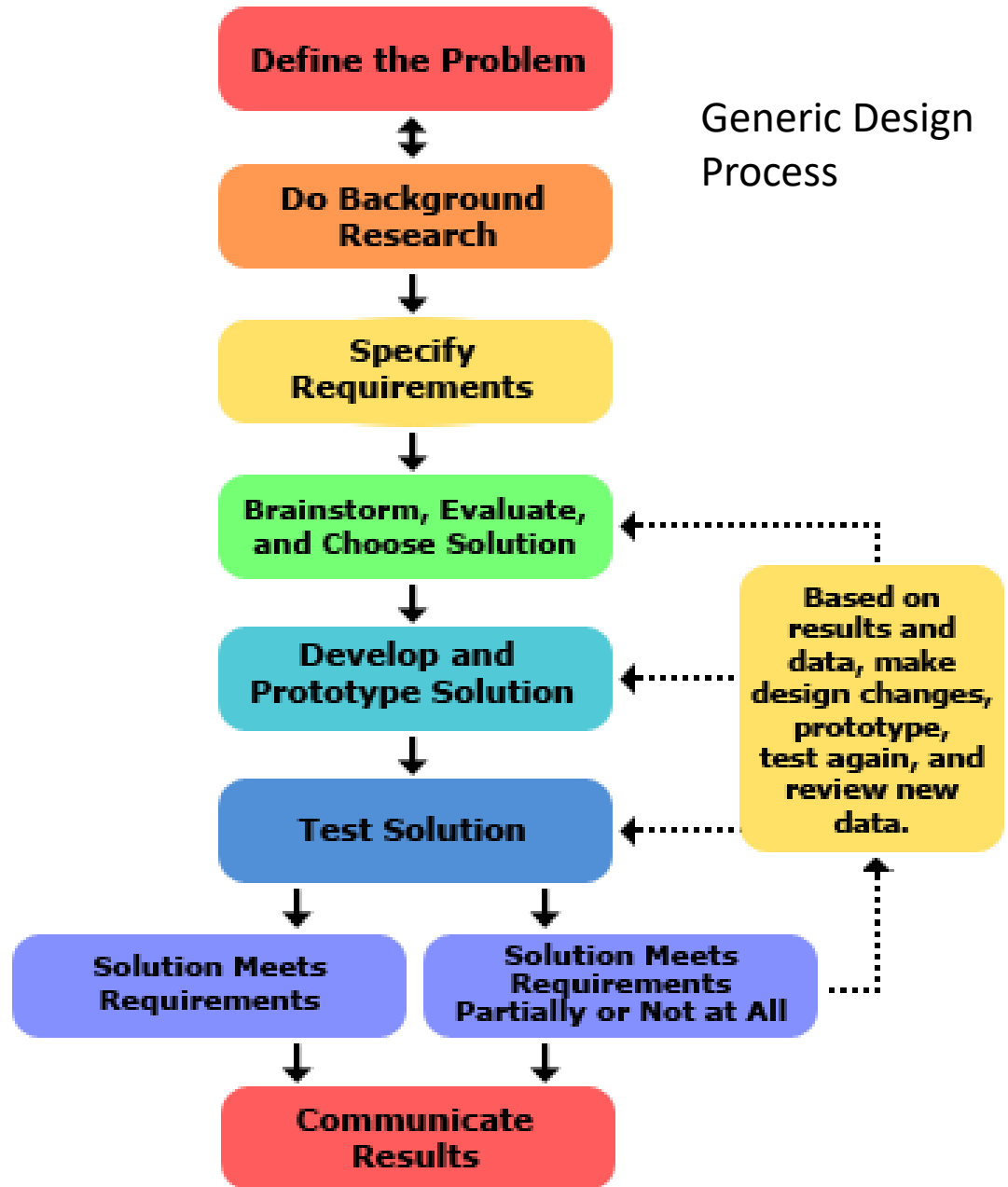


# Good Design Takes Time

- ...even for the pros. Relax, this is a timesink but a rewarding one.
- Estimate at least 6mo of regular use to really get competent with a big program like Blender, Solidworks, Zbrush, etc



Make  
prototypes,  
iterate your  
design



# Happy Designing!

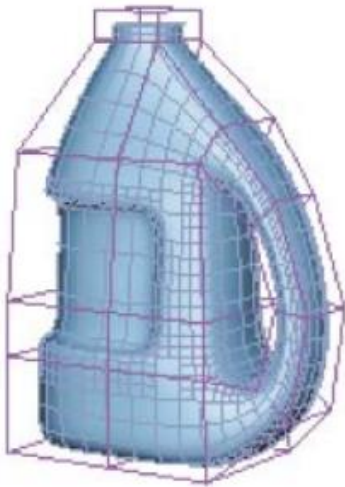


# Extra Credit Slides

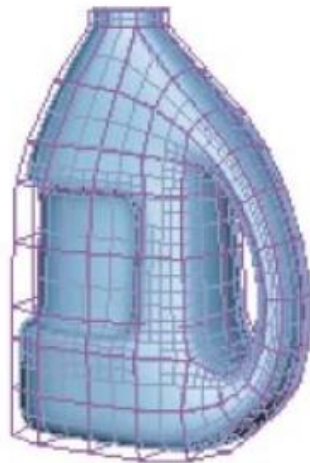


# SubD Modelling

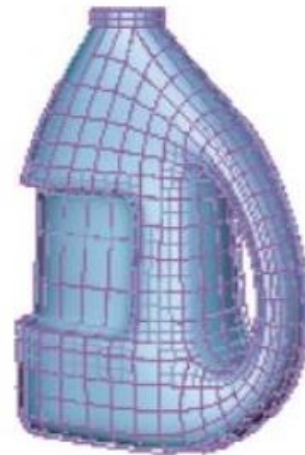
- Little personal experience so I'm not going to discuss much 😊
- Combines aspects of splines and polymesh
  - a mostly-quads control mesh is smoothed into curves by repeated subdivision into smaller polygons
  - Each level of subdivision acts as a control grid for the next level of subdivision, you can switch up and down levels as you edit
- Like T-splines, allows creation of complex models without patches
- Free, open-source subdivision modeling? → Blender!



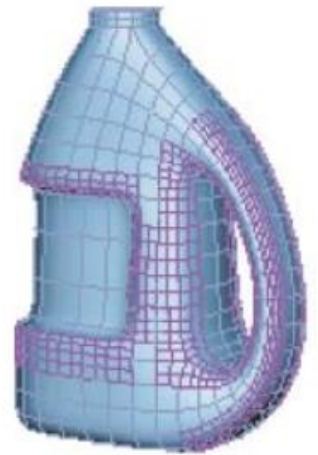
Subdivision Surface  
Level = 0



Subdivision Surface  
Level = 1



Subdivision Surface  
Level = 2



Subdivision Surface  
Level = 3



# Classic 3D CAD +/-

- Advantages
  - Great for defining shapes accurately
  - Tools to make nice 2D layouts/blueprints
  - Many different programs and plugins offering huge range of features...some include Solids/CSG
  - Familiarity with 2D vector CAD will help get you started
- Disadvantages
  - Tools aren't great for organic/artistic forms
  - Easy to make non-manifold and self-intersecting objects
  - Core function is blueprints and diagrams, not CAM/CAE

# CSG +/-

- Advantages
  - Combining shapes is fairly intuitive
  - Solid modelling → STL export “guaranteed” manifold
  - Ordered modelling very useful if you want to modify something later
- Disadvantages
  - Not great for artistic stuff
  - Somewhat limited by the 3D primitives available in that program.

# Feature-Based Direct +/-

- Advantages
  - Combination of different feature types gives a lot of flexibility to accurately define different shapes
  - Solid-based, so “guaranteed manifold” STL exports
  - Full-featured programs have powerful CAE and CAM
  - Most programs in this category emphasize intuitive commands and fast workflow
- Disadvantages
  - Tools aren’t great for organic/artistic forms
  - Large # of tools and ways to create can be overwhelming

# Feature-Based Ordered +/-

- Advantages
  - **History** very useful if you need to change something halfway through
  - **Parameters** powerful tool for creating multiple customized versions of a part
  - Like all feature-based solid CAD: flexibility to accurately define different shapes, “guaranteed manifold” STL exports, full-featured programs have powerful CAE and CAM
- Disadvantages
  - Steeper learning curve
  - For history and parameters to be useful, really need to take time planning order of features and relationships between parameters.
  - Complex models can become “fragile”: so many interdependent variables and constraints, changing anything breaks it.
  - Like all CAD: Tools aren’t great for organic/artistic forms, large # of tools and ways to create can be overwhelming

# Polygon Modelling +/-

- Advantages
  - Can move and modify faces freely; not limited by set of feature-based or boolean tools.
  - Edit commonly encountered file types such as .STL
  - Also used for animation and game modelling
- Disadvantages
  - Steeper learning curve
  - Polygons, so scaling up size = less smooth
  - Easy to create non-manifold and self-intersecting meshes
  - Tools not great for accurate design and engineering

# Digital Clay +/-

- Advantages
  - Relatively intuitive, easy to learn
  - Fastest way to make highly detailed models and organic/artistic shapes
  - Also used in animation and game modelling
- Disadvantages
  - can reach VERY HIGH # of polygons and file size
    - Can bog down or crash the your system
  - Polygons, so scaling up size = less smooth (although high poly count means you can scale a lot)
  - Can create non-manifold and self-intersecting meshes
  - Useless for accurate design and engineering



# Freeform Modelling +/-

- Advantages
  - Straddles the line between artistic modelling and CAD—make mathematically defined shapes that are also curvy/organic
  - Unlike polygon-based models, curves stay smooth as you scale up.
- Disadvantages
  - Manipulating splines is not super intuitive.
  - Lacks strong parametric and CAE tools.
  - Can't sculpt small texture details like you can with polymesh clay tools.
  - Easy to create self-intersection